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Original Article

The stepping test, and infrared depth sensor, provide reliable measures of balance in community-dwelling older adults

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Abstract. [Purpose] The purpose was to examine relationships between variables characterizing the 20-second stepping test movement pattern, assessed with an infrared depth sensor (Kinect^{TM}), and measurements of dynamic and static balance. [Participants and Methods] A total of 27 independent-living, older adults (7 males and 20 females) participated in this study. For each participant, the stepping test total movement distance, movement displacement, knee movement distance, and step number were calculated from Kinect closed joint-point coordinate data. Dynamic and static balance were assessed using a NeuroCom Balance Master Platform system. [Results] The stepping test total movement distance had a moderate negative correlation with endpoint excursion (r=−0.469) and a moderate positive correlation with total movement distance, corrected for knee movement distance (r=0.557). Step numbers had a moderate negative correlation with stepping test total movement distance (r=−0.667) and total movement distance, corrected for knee movement distance (r=−0.531). Division into high and low-balance subgroups (based on endpoint excursion or sway velocity scores) revealed that stepping test total movement distances and movement displacements were greater, and step numbers were fewer, in low balance groups. [Conclusion] The stepping test, combined with a Kinect^{TM}-assessed movement pattern provides a simple, objective, reliable means for assessing balance in community-dwelling, independent-living older adults.
Key words: 20-sec stepping test, Static balance, Dynamic balance

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INTRODUCTION

Aging is associated with changes in organ system functions that lead to loss of physiological reserve, and eventually limits responsiveness to stresses and dysfunctional regulation.

Frailty is a biological syndrome characterized by cumulative decline of multiple physiological system[1)]. The definition of frailty includes physical, cognitive, psychological, nutritional, and social constructs[2–4)]. Musculoskeletal integrity, generalized impaired walking, and reduced walking velocity are among such primary definitions of frailty syndrome[5)]. Although slow gait speed is nonspecific and multifactorial[5–8)], it is predictive of the disability of activities of daily living (ADLs)[9)], dementia risk[10)], cardiovascular disease, and cardiovascular and all-cause mortality[11–13)]. Thus, functional independence is highly reliant on ability to walk.

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Postural control and balance are critical for stable gait and maintenance of gait velocity; yet, age negatively affects both[14–20)]. Balance may be the ultimate factor in determining gait speed and fall prevention[21–23)].

In recent years, the explosion of technological advances in computing power, monitoring (“smart”) devices, and wireless technology has led to development of noninvasive, unobtrusive methodologies for quantitative evaluation of movement dysfunction towards early detection of frailty (for extensive review see[24)]). Specific to the present study, infrared depth sensors (Kinect™) have demonstrated effective ability for analyzing human movement[25, 26)] and postural sway[27)], providing at a low cost (remove comma) and relatively simple means for assessment of human physical function. Recently, it was shown that movement path length and movement displacement quantified with an infrared depth sensor during a 20-sec stepping-in-place test (ST) provided strong discriminatory data towards identifying need for ADL assistance in distinguishing community-dwelling independent-living individuals from assisted-living dependent individuals[28)]. ST movement variables showed moderate sensitivity (0.67–0.76) and specificity (0.73–0.84) in predicting dependent, assisted living with negative predictive values from 75–81% and few false negatives[28)]. It was speculated that variables describing ST movement pattern were assessing balance because stepping-in-place was a series of single-leg stance intermixed with leg-to-leg transitions as in gait. Thus, the present purpose was to assess relationships between ST variables (e.g., movement path length, movement displacement, and knee movement distance) and quantitative laboratory assessments of dynamic and static balance.

PARTICIPANTS AND METHODS

Asahi University Ethical Committees (#2017011, #202002) reviewed and approved this study, which was conducted in accordance with Declaration of Helsinki guidelines and current laws of Japan. Participants received oral and written instructions concerning testing and each gave oral and written informed consent prior to participation. The individuals shown in Figs. 1 and 2 have given informed consent for the use of their image.

This study was conducted in the local area of west Japan. Participants were recruited from a community-based well-rounded exercise program (combined walking, band-based resistance, balance and flexibility) in Yasugi City (Shimane Prefecture) and Kofu Town (Tottori Prefecture), Japan. Participants who were active and healthy, with no history of falling were included. All participants were freely ambulatory without use of any mechanical or physical assistance. All participants completed two trials of the stand-up and go test prior to inclusion to assure physical independence.

Community-dwelling independent older adults (N=27; male: n=7, female: n=20) between 55 and 85 years completed a 20-sec ST as wells as dynamic and static balance tests. Prior to the ST, degree of functional independence was assessed by Functional Independence Measure (FIM). Participant characteristics are presented in Table 1. Height (m) and body mass (kg) were measured using a body fat analyzer (TANITA TBF-202; Tanita Co., Tokyo, Japan) and body mass index (BMI) was calculated (body mass divided by height^2). FIM assesses level of disability, consisting of 18 items, scored on a 7-level classification from complete independence to complete dependence[34)]. FIM scores range from 18 to 126 with higher scores indicating higher levels of functional independence. The same physical therapist conducted and scored all FIM testing.

Then, participants completed a 20-sec ST with eyes open as previously described in detail[28)]. Briefly, individuals alternatively raise their knees, stepping in place at a self-selected stepping pace. Joint point coordinate data were collected with a Microsoft Kinect™v2 (hereafter Kinect™;[25)]) during the final 10 sec of the ST.

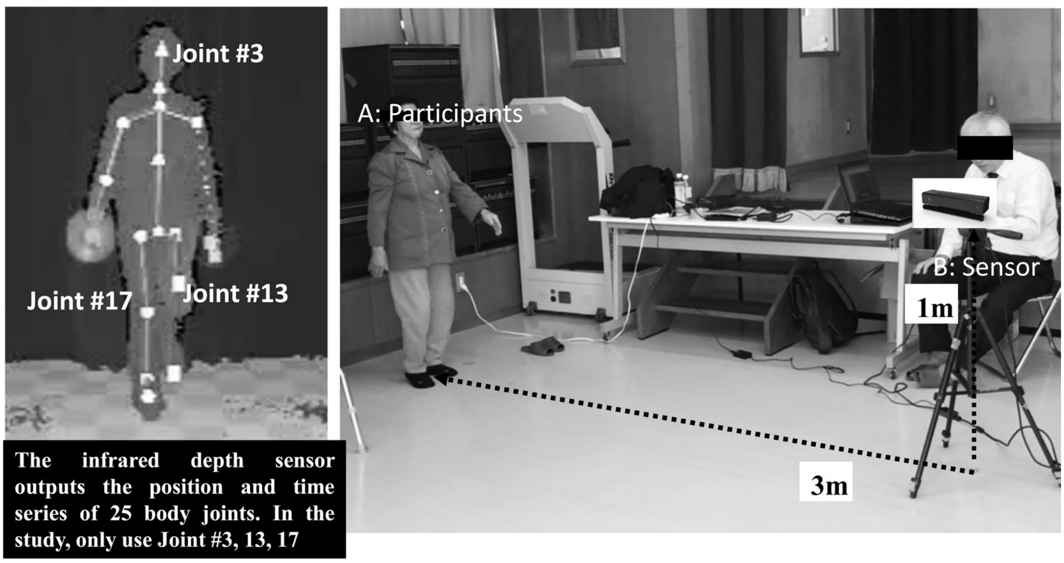

Fig. 1. 20-sec stepping test (ST) using Kinect™ sensor.

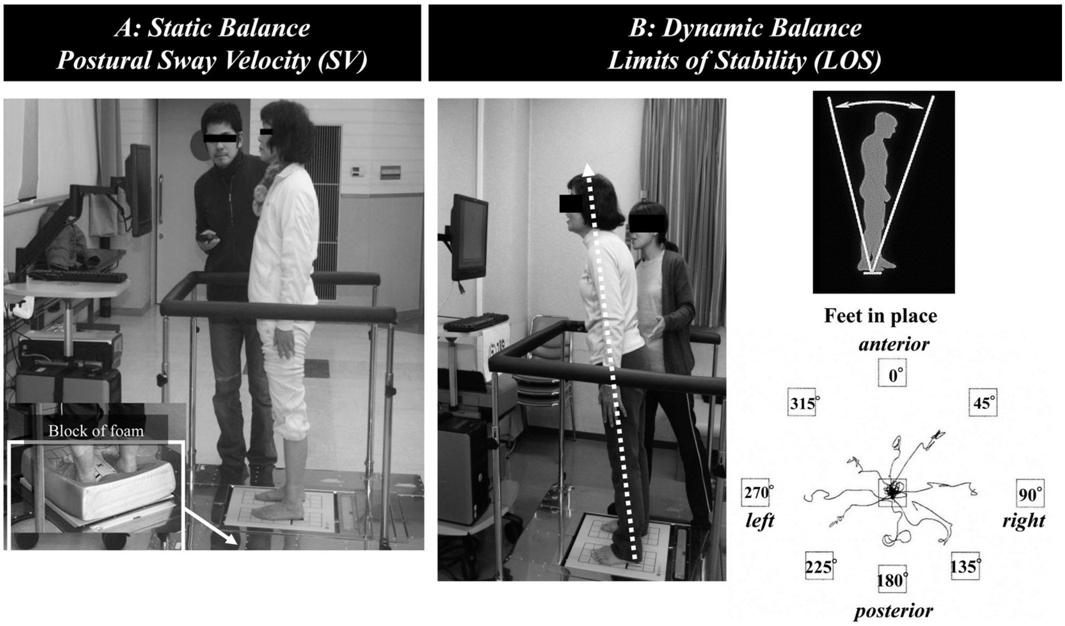

Fig. 2. Static (A: Postural Sway Velocity) and dynamic balance test (B: Limits of Stability) using Balance Master platform system.

Table 1. Participant characteristics for the sample population sway velocity, limits of stability (LOS), step test movement distance and displacement data and by gender

		All (n=27)			Male (n=7)			Female (n=20)		
		Mean ± SD	Max	Min	Mean ± SD	Max	Min	Mean ± SD	Max	Min
Age (years)		74.7 ± 7.1	85	55	78.0 ± 4.6	85	72	73.6 ± 7.7	84	55
Height (cm)		153.5 ± 7.3	174.9	143.2	161.5 ± 7.3*	174.9	152.0	150.8 ± 5.2	162.0	143.2
Body mass (kg)		55.1 ± 8.0	80.0	44.0	62.8 ± 10.6*	80.0	53.0	52.4 ± 5.2	60.4	44.0
BMI (kg/m^2)		23.3 ±2 .7	29.4	17.3	24.1 ± 4.0	29.4	17.3	23.1 ± 2.2	26.9	18.3
Static Balance, Sway Velocity	SV (°/sec)	0.97 ± 0.35	2.30	0.50	1.06 ± 0.22	1.30	0.70	0.94 ± 0.39	2.30	0.500
Dynamic Balance,	RT (sec)	0.85 ± 0.21	1.30	0.54	0.83 ± 0.20	1.09	0.56	0.84 ± 0.23	1.30	0.540
Limits of Stability	MVL (°/sec)	4.5 ± 1.3	7.9	1.8	5.0 ± 2.0	9.4	3.5	4.7 ± 1.5	7.9	1.8
(LOS)	DCL (%)	80 ± 3	82	76	78 ± 5	82	70	80 ± 4	87	72
Step Test Movement	TMD (m)	0.812 ± 0.219	1.417	0.472	0.994 ± 0.311*	1.417	0.656	0.749 ± 0.146	1.066	0.472
Distance and	MMD(m)	0.193 ± 0.073	0.332	0.0.79	0.249 ± 0.084*	0.332	0.137	0.174 ± 0.065	0.306	0.080
Displacement Data	KMD (m)	4.429 ± 1.23	7.668	2.363	4.306 ± 0.923	6.041	3.533	4.472 ± 1.373	7.667	2.362
	STEP (steps)	17 ± 2	22	11	16 ± 3*	18	11	18 ± 2	22	13
	TMD/ht (m/m)	0.006 ± 0.01	0.009	0.003	0.006 ± 0.002*	0.009	0.004	0.005 ± 0.001	0.007	0.003
	MMD/ht (m/m)	0.001 ± 0.004	0.0021	0.0005	0.002 ± 0.005	0.002	0.009	0.001 ± 0.001	0.002	0.001
	TMD/STEP (m/step)	0.049 ± 0.216	0.1248	0.0262	0.067 ± 0.033*	0.125	0.036	0.043 ± 0.017	0.077	0.026
	MMD/STEP (m/step)	0.012 ± 0.005	0.023	0.004	0.016 ± 0.006*	0.023	0.008	0.0099 ± 0.004	0.016	0.0044
	TMD/KMD (m/m)	0.196 ± 0.068	0.353	0.089	0.230 ± 0.049	0.297	0.170	0.184 ± 0.072	0.353	0.089

*Men significantly different from women, $p \leq 0.05$.
BMI: body mass index: body mass (kg)/height (m)^2; SV: sway velocity; RT: reaction time; MVL: average movement velocity; DCL: directional control; TMD: total movement distance in meters; MMD: maximum movement displacement in meters; KMD: knee movement distance; STEP: step count; ht: height.

Kinect™ sensor irradiates pulse-modulated infrared light using a special infrared projector that converts depth distance of participant's joints by obtaining the timing of reflected light sensed by the infrared camera; termed "Time of Flight" method. The infrared depth sensor outputs a position-time series of 25 body joints (Fig. 1 shows 17 such points) in three-dimensional space[25]. Accuracy and validity of the Kinect™ sensor is sufficient for movement analysis and quantification of movement pattern during ST[25].

For testing, the Kinect™ sensor was fixed using a tripod with the center of the camera 1.0 m from the floor and 3.0 m from the participant (Fig. 1). A MB-V700X-BK2 laptop (Mouse Computer Co. Ltd., Tokyo, Japan) served as the host computer. Interface requirements include: CPU Core i7 (4 cores), clock 2.5 GHz, RAM 24 GB, HDD 120 GB, SSD 1 TB, USB3.0, Screen 1920 × 1080. Kinect™ sampling frequency was 30 fps.

The basis for quantifying ST performance and movement pattern in this study is defined by four primary variables: total movement distance (TMD), movement displacement from starting position (MMD), and sway index (TMD/KMD) and step number. TMD (Fig. 1, Joint number 3) is total linear distance (m) determined from the sum total of step-by-step changes in Joint number 3 position from its initial to its final position (Fig. 3). MMD is the maximum displacement of the head (Fig. 1, Joint number 3) along the movement path from its initial position (Fig. 3). TMD and MMD were defined as follows:

$$TMD = \sum_t \|\boldsymbol{H}(t) - \boldsymbol{H}(t-1)\|,$$

$$MMD = \max_t \|\boldsymbol{H}(t) - \boldsymbol{H}(0)\|,$$

where $\boldsymbol{H}(t)$ and $\boldsymbol{H}(0)$ are the 3D head coordinate at an arbitrary time t and at the ST starting point, respectively. $\|\boldsymbol{H}(t) - \boldsymbol{H}(t-1)\|$ and $\|\boldsymbol{H}(t) - \boldsymbol{H}(0)\|$ indicates the Euclidean distance between two points in time. Sway index is TMD corrected for the average movement distance of the left and right knees (KMD) during stepping (i.e., Sway index=TMD/KMD). KMD is determined from left and right knee joint points (Fig. 1, Joint numbers 13 and 17). Locus length of each knee was calculated as the sum total of three-dimensional movements of each knee joint points during stepping. Let $\boldsymbol{K}^L(t)$ and $\boldsymbol{K}^R(t)$ be the left and right knee coordinate points at time t, respectively. Total movement of left and right knee joint points (KMD) are defined as follows:

$$K_{sum}^L = \sum_t \|\boldsymbol{K}^L(t) - \boldsymbol{K}^L(t-1)\|,$$

$$K_{sum}^R = \sum_t \|\boldsymbol{K}^R(t) - \boldsymbol{K}^R(t-1)\|,$$

$$KMD = \frac{K_{sum}^L + K_{sum}^R}{2}.$$

This sway index (TMD/KMD) provides an index of upper-body sway relative to the lower body. Lastly, step number is the total number of foot contacts beginning with the return of the right foot to the ground after raising the right leg to initiate the test. Stepping rate is inferred from step number divided by 10 sec (constant duration of Kinect™ data collection).

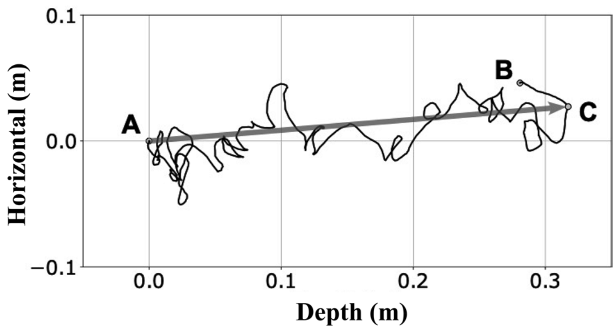

Fig. 3. Graph of stepping test (ST) movement pattern and point demarcations for measuring total movement distance (TMD) and maximum movement displacement (MMD) TMD is the total linear length of the movement of the head joint point from its initial (A) to final (B) position. Maximum movement displacement (MMD) is the greatest single point displacement of the head joint point 3 along the movement path from its initial (A) to maximal distance (C) position.

To address our research question, participants completed dynamic and static balance testing using the NeuroCom Balance Master Platform system (NeuroCom International, Clarckamas, OR, USA; Fig. 2). Balance, loosely defined, is some combination of dynamic and static balance although typically assessed independently. Dynamic balance reflects an ability to anticipate postural changes through coordination of muscle activity in response to stability perturbations, while postural sway during quiet standing provides specific quantification of static balance. The Balance Master Platform system provides measures of both dynamic and static balance, and is widely used to study balance (e.g.[27, 29–33]), including previous work from our laboratory[15)].

Limits of stability (LOS) assessment characterized dynamic balance. Details of testing method are as described previously[15, 31–33)]. Briefly, eight trials consisting of sequential appearance of targets on the computer screen around a center square at 0, 45, 90, 135, 180, 225, 270 and 315°; Fig. 2). Each trial began with target appearance. Center of pressure appeared as a cursor and moved as participants shifted their weight toward an identified target, then holding target position for 8 s.

For each LOS trial, an end-point excursion (EPE) and maximum excursion (MXE) relative to each target was determined. EPE is displaced center of pressure (COP) toward the target during the participant's primary movement. This movement segment ends when COP movement first ceases progression toward the target, expressed as a percentage of target distance. Hence, if initial movement ends precisely at the target, EPE=100%. When initial attempts do not attain the target, most people initiate additional movements recorded after EPE. This additional movement (COP excursion), toward the target over the entire duration of the trial is termed MXE, expressed as a percentage of target distance. MXE may be greater or lesser than EPE depending on whether the participant acquired the target on initial movement. Reaction time (RT, sec) is time between signal to move and movement initiation. Movement velocity (MVL, °/sec) is the average COP velocity over the trial. Directional Control (DCL, %) is defined as percentage of intended movement relative to a straight-line path to the target and corrected for unintended movement; movement away from the target. EPE, MXE, RT, MVL, and DCL scores averaged over eight targets produced composite scores used for statistical analysis. Calculating MXE/EPE using composite scores provides an indicator of the magnitude of corrective movements ultimately required to attain targets.

Postural sway velocity (SV) characterized static balance and was measured during quiet standing in four conditions; eyes open (EO) and closed (EC) while standing on the floor or a block of foam (46 × 46 × 13 cm; Fig. 2) as described previously[15)]. Trials required 10 s data collection. A trial was unsuccessful, and repeated, if participant took a step or was unable to balance without aid for the required time interval. Participants stood with their eyes at the horizon and arms in a relaxed, neutral position at their sides for each trial. Force platform was marked to assure consistent foot placement. Sway velocity (SV) averaged over all four conditions provided a composite static balance score used for analysis.

ST test-retest reliability was assessed using one-way ANOVA and intraclass correlation[35, 36)]. EPE and MXE by angle curves were plotted to visualize dynamic balance and analyzed with a repeated measures ANOVA across in one domain (LOS angle). Study population relationships between ST measures dynamic (EPE and MXE composite scores) and static (SV composite scores) and balance were explored using Pearson Product-Moment correlation.

To further address our study question concerning the relationship between ST data and balance, the study population was sub-divided into groups based on EPE and SV composite scores. Using EPE as a criterion measure of dynamic balance, participants with the highest (EPE-High; n=6) and lowest (EPE-Low; n=6) EPE composite scores were divided into groups. Likewise, using SV as a criterion measure for static balance, participants with the highest (SV-High; n=6) and lowest (SV-Low; n=6) SV composite scores were divided into groups. Differences between high- and low-balance groups were assessed with a two-way ANOVA with repeated measures in LOS angle, while between groups differences in ST variables were analyzed with a one-way ANOVA. *Apriori* p-value for statistical significance in all ANOVA and correlation analyses was set at $p \leq 0.05$. Interpretation of strength of association between variables (correlation coefficients) are presented as very strong >0.90, strong 0.70–0.89, moderate 0.40–0.69, and weak 0.10–0.39[37)].

RESULTS

All participants scored a 126 on the FIM test indicating highest possible functional independence.

There were no between trial differences in TMD (2.355 ± 0.877 vs. 2.114 ± 0.618 m, respectively), MMD (0.417 ± 0.109 m vs. 0.355 ± 0.117 m, respectively), KMD (6.740 ± 3.525 vs. 5.794 ± 2.048 m, respectively) or step number (34 ± 7 vs. 33 ± 5, respectively). Repeat trial ICC's were very strong for TMD (ICC=0.96), strong for KMD (0.77) and step number (0.85), and moderate for MMD (0.64).

Age had a moderate positive correlation with RT (r=0.558, p=0.002). All other correlations between age and balance and ST variables were weak or negligible (r range 0.319 to −0.307, p>0.05). EPE averaged 82 ± 14% while MXE averaged 99 ± 10% indicating that, on average, participants ultimately acquired targets, but with large variability in EPE and MXE (Fig. 4). Likewise, MXE/EPE was quite variable (range of 1.02 to 1.73), averaging 1.24 ± 0.17%. EPE and MXE were moderately correlated (r=0.696, p<0.001), with no differences between respective LOS performance (Fig. 4); except initial EPE and MXE (0° angle) being less than all other values. MXE/EPE had a strong negative correlation with EPE (r=−0.802, p=0.001) and a moderate positive correlation with SV (r=0.498, p=0.008), height (r=0.462, p=0.015).

Population performance during LOS and postural stability testing showed wide variation (Table 1). LOS movement velocity (MVL) showed moderate positive correlations with EPE (r=0.624, p<0.001) and MXE (r=0.684, p<0.001), a weak nega-

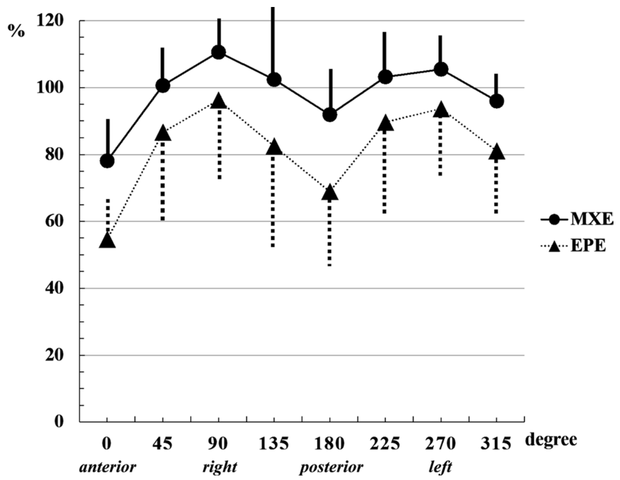

Fig. 4. Endpoint Excursion (EPE) and Maximum Excursion (MXE) curves for the entire population.

tive correlation with MXE/EPE (r=−0.264, p=0.183) and a weak positive correlation with SV (r=0.327, p=0.096). RT was weakly negatively correlated with MXE (r=−0.398, p=0.040) and weakly positively correlated with EPE (r=0.265, p=0.381). Correlations between DCL and EPE (r=0.078, p=0.700), MXE (r=−0.078, p=0.700) or MXE/EPE (r=−0.229, p=0.250) were weak. SV had a moderate positive correlation with MXE/EPE (r=0.498, p=0.008), a weak positive correlation with MXE (r=0.251, p=0.209), and a weak negative correlation with EPE (r=−0.253, p=0.202) and DCL (r=−0.360, p=0.065).

As with balance testing, ST performance variables showed wide variation (Table 1). TMD had a moderate, negative correlation with EPE (r=−0.469, p=0.014) and moderate positive correlations with MXE/EPE (r=0.546, p=0.003) and TMD/KMD (r=0.557, p=0.003). MMD had a weak, negative correlation with EPE (r=−0.368, p=0.058) and weak positive correlations with MXE/EPE (r=0.326, p=0.097), and TMD/KMD (r=0.322, p=0.102).

Step number had moderate, negative correlations with TMD (r=−0.667, p=0.001), MXE/EPE (r=−0.448, p=0.019), TMD/KMD (r=−0.531, p=0.004), but had a weak positive correlation with EPE (r=0.349, p=0.075). TMD and MMD were moderately, positively correlated (r=0.460, p=0.016). TMD (r=0.427, p=0.013), but not MMD (r=0.203, p=0.238) had a moderate, positive correlation with height. Height was moderately, negatively correlated with EPE (r=−0.425, p=0.027) and step number (r=−0.467, p=0,014), but, moderately, positively correlated with MXE/EPE (r=0.462, p=0.008).

By dynamic balance definition, EPE-High had greater EPE (101 ± 6%) and LOS performance than EPE-Low (EPE=62 ± 6%) with no difference at initial angle (moving forward, 0°; Fig. 5). MXE was also greater in EPE-High (108 ± 5%) than EPE-Low (88 ± 7%; Fig. 5). MXE/EPE was significantly greater in EPE-Low (1.42 ± 0.23) than EPE-High (1.07 ± 0.04). MVL was greater and SV lesser in EPE-High (Table 2). RT and DCL were not different between EPE balance groups (Table 2).

TMD and MMD were greater and step number was lesser in EPE-Low (Table 2). MMD/step number was greater and TMD/step number tended (p=0.061) to be greater in EPE-Low (Table 2). KMD and TMD/KMD were similar between groups (Table 2). EPE-Low was taller and tended to be older (p=0.053) than EPE-High, while body mass and BMI were similar (Table 2).

By static balance definition, SV was greater in SV-High (Table 3). There were no differences in dynamic balance (LOS testing variables) between SV-High and SV-Low (Table 3). However, MXE/EPE was significantly greater in SV-High (1.27 ± 0.13%) vs. SV-Low (1.10 ± 0.04%). TMD/KMD was the only ST variable that differed between SV-High (0.238 ± 0.034 m/m) and SV-Low (0.149 ± 0.038 m/m; Table 3). Age, height, and body mass were similar, but BMI was greater in SV-Low (Table 3).

Male and female were similar in age, with men being taller with greater body mass, but BMI was similar (Table 1). EPE and MXE (Fig. 6) performance were similar in male and female with composite EPE (77 ± 18%, 84 ± 2%, respectively) and MXE (94 ± 10%, 100 ± 9%, respectively) scores being similar. There were no gender-specific differences in RT, MVL, and DCL (Table 1). TMD and MMD were greater, and step number was lesser, in male (Table 1). When corrected for height or step number, TMD/ht, but not MMD/ht and TMD/step number was greater in male (Table 1). TMD/KMD was similar in male and female (Table 1).

DISCUSSION

Primary findings of the present study indicate that in a sample population of independent living, community-dwelling older adults, balance, and ST variables vary widely and exhibit weak associations with age, yet, primary ST variables are

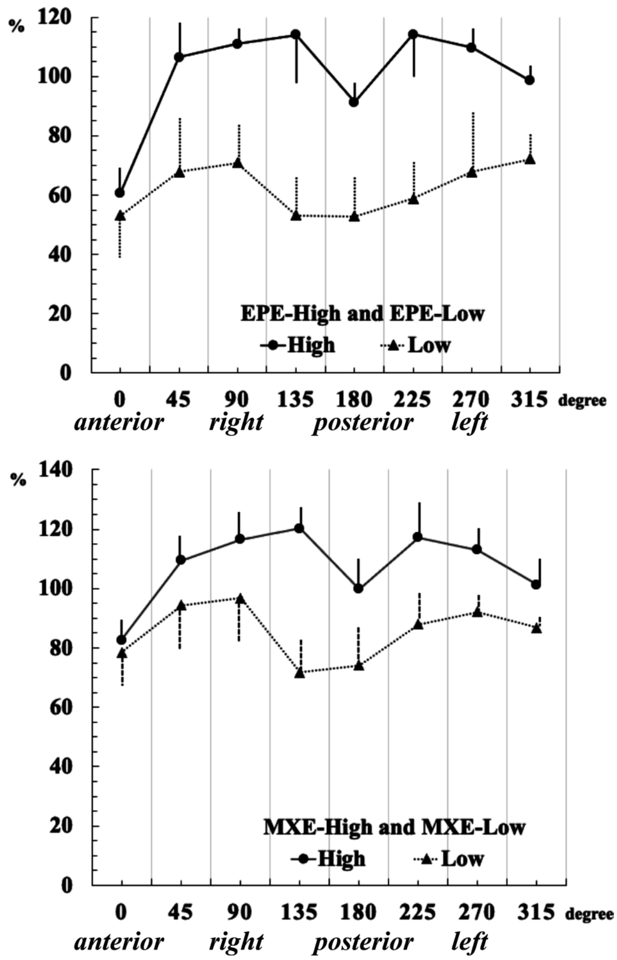

Fig. 5. Endpoint Excursion (EPE) and Maximum Excursion (MXE) for balance subgroups.

associated with, and differentially discriminate, low- and high-levels of dynamic balance (EPE) and static (sway velocity) balance. MVL and RT appear as significant factors distinguishing dynamic balance and these variables are significantly associated with ST performance. Lastly, preliminary test-retest analysis shows strong association between repeat trials of the ST.

While EPE scores were generally high, indicating initial balance movements were good on average, many participants required correction to acquire targets. There was wide variation in both EPE and MXE and neither was associated with age, in agreement with previous work in a similar age population[30]. Wide variation in EPE, MXE, and movement error (MXE/EPE) attaining targets, leads to a conclusion indicating a continuum of balance function/dysfunction and presence of compensations for balance deficits (MXE/EPE) in this population of independent-living, older adults. This apparent balance continuum here is unrelated to age and gender. That balance varies, even within a population of higher functioning, independent-living older adults is suggestive of compensations to adjust for varying levels of balance dysfunction to maintain the ability to live independently.

As one of the two apparent primary compensations for balance deficits noted during LOS testing, slower MVL was associated with EPE and MXE and was greater in the EPE-High group. Lesser step number and, thus, slower stepping rate was associated with poor balance, distinguishing EPE-High from EPE-Low balance. ST movement distance (TMD) and displacement (MMD) had no direct association with LOS MVL, but EPE-High individuals had greater LOS MVL and lesser TMD and MMD than EPE-Low. ST movement velocity was greater in EPE-High, as indicated by greater step number, and therefore, stepping rate. This observation is consistent with our recent finding that lower step number and stepping rate distinguished ADL-deficient, dependent-living individuals in need of care[28]. Likewise, stepping at a significantly slower rate during a fixed, single-leg step-numbering task was observed in community-living older adults with a history of falling[38]. Thus, there is an apparent slowed movement velocity compensation as indicated by lower ST stepping rate. As a compensation 'designed' to improve balance and function, fewer steps and lower stepping rate reflect slowed movement speed as with slowed gait speed[6–8] and the consistent finding in individuals with poor balance[6, 20] and increased risk of falling[21, 39–42]. Further, slow movement speed is a strong predictor of ADL disability[9] and frailty[5].

Table 2. Participants characteristics and static/dynamic balance and step test movement distance and displacement data in EPE-High vs. EPE-Low dynamic balance groups

		EPE-High (n=6)			EPE-Low (n=6)		
		Mean ± SD	Max	Min	Mean ± SD	Max	Min
Age (years)		70.2 ± 5.2†	79	65	77.4 ± 5.5	85	72
Height (cm)		152.8 ± 6.9*	165.0	144.0	163.1 ± 6.9	174.9	158.1
Body mass (kg)		55.9 ± 12.8	80.0	44.0	60.7 ± 8.3	74.5	53.00
BMI (kg/m^2)		23.7 ± 3.2	29.4	20.9	23.0 ± 3.8	27.9	17.3
Static Balance, Sway Velocity	SV (°/sec)	0.85 ± 0.22*	1.20	0.60	1.16 ± 0.09	1.30	1.10
Dynamic Balance, Limits of Stability (LOS)	RT (sec)	0.680 ± 0.036	0.730	0.630	0.838 ± 0.240	1.090	0.560
	MVL (°/sec)	6.5 ± 1.6*	9.4	5.2	3.9 ± 0.5	4.6	3.5
	DCL (%)	79 ± 5	84	70	78 ± 4	82	72
	MXE/EPE	1.07 ± 0.04*	1.13	1.01	1.42 ± 0.23	1.73	1.36
Step Test Movement Distance and Displacement Data	TMD (m)	0.766 ± 0.124*	0.921	0.591	1.083 ± 0.329	1.416	0.673
	MMD (m)	0.180 ± 0.777*	0.271	0.088	0.285 ± 0.040	0.332	0.239
	KMD (m)	4.232 ± 1.576	7.200	2.6073	4.311 ± 1.337	6.041	2.521
	STEP (steps)	18 ± 1*	20	16	15 ± 3	18	11
	TMD/ht (m/m)	0.0050 ± 0.0013	0.0062	0.0047	0.0066 ± 0.0018	0.0087	0.0044
	MMD/ht (m/m)	0.0012 ± 0.0005†	0.0018	0.0006	0.0018 ± 0.0003	0.0021	0.0014
	TMD/STEP (m/step)	0.044 ± 0.033†	0.054	0.035	0.075 ± 0.036	0.125	0.039
	MMD/STEP (m/step)	0.010 ± 0.005*	0.017	0.004	0.019 ± 0.003	0.023	0.014
	TMD/KMD (m/m)	0.200 ± 0.081	0.353	0.119	0.255 ± 0.046	0.297	0.187

p≤0.05, †p=0.06; BMI: body mass index: body mass (kg)/height (m)^2. SV: sway velocity; RT: reaction time; MVL: average movement velocity; DCL: directional control. *Groups as determined by highest (EPE-High) and lowest (EPE-Low) EPE scores. MXE: maximum excurtion; EPE: endpoint excurtion; TMD: total movement distance in meters; MMD: maximum movement displacement in meters; KMD: knee movement distance; STEP: step count; ht is height; SD: standard deviation.

Table 3. Participants characteristics and static/dynamic balance in SV-High vs. SV-Low static balance groups

		SV-Low (n=6)			SV-High (n=6)		
		Mean ± SD	Max	Min	Mean ± SD	Max	Min
Age (years)		71.3 ± 13.7	84	55	78.2 ± 4.7	85	73
Height (cm)		151.1 ± 3.2	155.0	147.5	154.0 ± 6.9	162.0	143.2
Body mass (kg)		58.0 ± 1.9	60.4	55.8	53.0 ± 5.3	60.3	45.9
BMI (kg/m^2)		25.4 ± 1.2*	26.9	24.1	22.4 ± 2.2	24.4	18.3
Static Balance, Sway Velocity	SV (°/sec)	0.575 ± 0.050*	0.600	0.500	1.450 ± 0.423	2.300	1.200
Dynamic Balance, Limits of Stability (LOS)	RT (sec)	0.865 ± 0.255	1.230	0.680	0.903 ± 0.166	1.090	0.690
	MVL (°/sec)	4.9 ± 2.4	7.3	1.8	5.8 ± 2.3	9.4	4.0
	DCL (%)	81 ± 5	86	76	76 ± 4	82	70
	MXE/EPE	1.10 ± 0.04*	1.15	1.07	1.27 ± 0.13	1.03	1.04
Step Test Movement Distance and Displacement Data	TMD (m)	0.726 ± 0.205*	0.921	0.472	0.964 ± 0.253	1.417	0.772
	MMD (m)	0.224 ± 0.364*	0.307	0.151	0.560 ± 0.061	0.332	0.168
	KMD (m)	4.979 ± 1.579	7.201	3.480	4.054 ± 0.882	4.831	2.790
	STEP (steps)	18 ± 2	19	15	16 ± 2	17	13
	TMD/ht (m/m)	0.0048 ± 0.0014	0.0061	0.0030	0.0063 ± 0.0016	0.0090	0.0049
	MMD/ht (m/m)	0.0015 ± 0.0005	0.0021	0.0010	0.0017 ± 0.0004	0.0021	0.0010
	TMD/STEP (m/step)	0.042 ± 0.016	0.061	0.026	0.063 ± 0.022	0.101	0.044
	MMD/STEP (m/step)	0.013 ± 0.003	0.016	0.008	0.017 ± 0.003	0.021	0.012
	TMD/KMD (m/m)	0.149 ± 0.038*	0.206	0.119	0.238 ± 0.034	0.293	0.201

*p≤0.05, Groups as determined by highest (SV-High) and lowest (SV-Low) sway velocity scores. BMI: body mass index; SV: sway velocity; RT: reaction time; MVL: average movement velocity; DCL: directional control; MXE: maximum excurtion; EPE: endpoint excurtion; TMD: total movement distance in meters; MMD: maximum movement displacement in meters; KMD: knee movement distance; STEP: step count, and ht is height; SD: standard deviation.

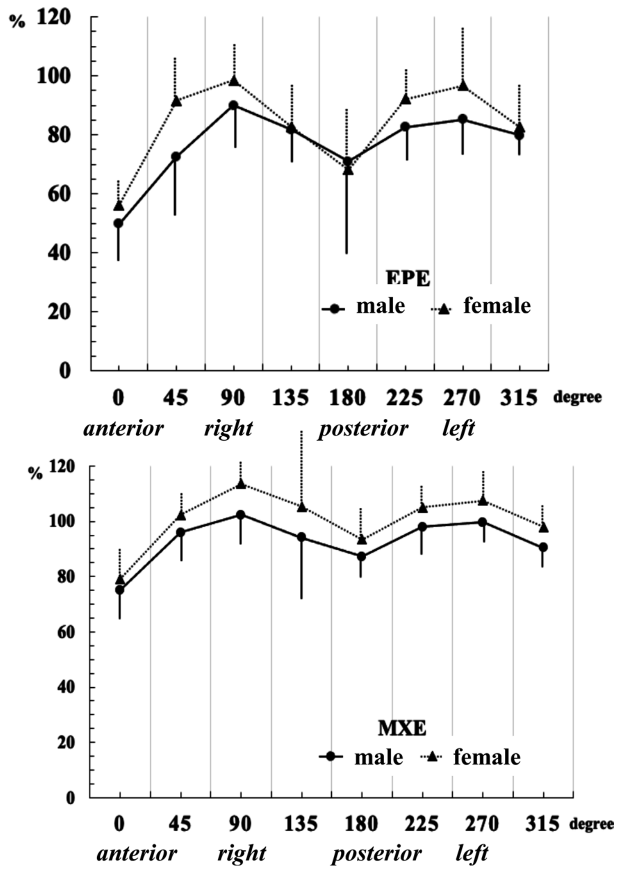

Fig. 6. Gender-specific graphs of Endpoint Excursion (EPE) and Maximum Excursion (MXE).

The significance of lesser step number and slower stepping rate being an indicator of balance dysfunction is the contrast that fewer steps produced a greater TMD and MMD in EPE-Low, even when corrected for step number. This is consistent with our previous observation in ADL-deficient, dependent-living individuals[28]. Additionally, there is a significant negative association between MXE/EPE (target acquisition error) and step number in the overall sample population and MXE/EPE was greater in EPE-Low and SV-High balance groups. Thus, individuals with a lower step number must deviate farther from initial position per step, indicating aberrant step replacement and leading to greater TMD and MMD; a clear indication of impaired balance.

A possible mechanism for aberrant step replacement and poor balance may be force control of muscles associated with balance[43]. While standing balance is primarily associated with muscles (dorsi- and plantar flexors), forces, and reflexes[44, 45] across the ankle joint, increasing evidence indicates a significant role for hip abductor/adductors[43, 46–48]. Activation of dorsiflexors and hip abductors explains sway-area rate and balance during standing[38, 43], but more specifically, force control of these muscles appears to control fontal plane motion, contributing to balance[43]. Consistent with the original Fukuda test[49], ST is a sagittal plane movement such that forward TMD movement without MMD is considered a 'normal' finding, not necessarily indicative of balance dysfunction. Although, ST is a sagittal plane movement, the presence of MMD indicates that movement TMD is away from center and in the frontal plane. It would appear that the impetus to move away from center during ST may be initiated by aberrant dorsiflexors and/or hip abductors force control, following from the work of Davis et al[43]. Certainly, understanding the link between muscle activation and force control relative to ST performance and balance assessment requires additional investigation.

A second possible explanation for aberrant step replacement relates to the other primary compensation for balance deficits noted during LOS testing, RT. Although, the relationship between age and dynamic/static balance was weak, the relationship indicating increased RT with age was significant; consistent with previous work[50–52] and slower RT during a single repetition step numbering task[38]. Additionally, RT tended to be greater in EPE-Low balance group. Slow RT indicates increased central processing associated with planned movement, and perhaps, associated with apprehension to move. Previously, we have shown that midline-crossing inhibition "reappears" in older individuals (>70 years) and that slow RT was indicative of increased central processing associated with apprehension to cross the body's midline[51]. The "reluctance" or slowed crossing of body midline is important in this context, as cross stepping appears to be the preferred strategy for regaining balance following balance perturbation[46, 53]. Cross stepping is also associated with reduced risk of falling and fall experience[53]. Reluctance to cross the body midline may contribute to lesser ST step number and stepping rate as a compensation for impaired balance. Ultimately, delayed RT during dual-task operations with sustained attentional focus may contribute to balance dysfunction and slowed walking speed[7, 50]. The apparent relationship between midline-crossing inhibition, step recovery strategy, and ST performance relative to assessing balance requires further investigation.

Lastly, poor static balance, indicated by postural sway, is a major risk factor for falling and increased SV is associated with increased falling and risk of falling[20, 38, 42]. ST sway index, indicated by TMD/KMD, significantly correlated with SV across the sample population and distinguished between individuals in SV-Low vs. SV-High balance groups. Likewise, the SV-High group had significantly greater TMD and MMD. Although, EPE and SV were not associated in the general population sample, SV was significantly greater in EPE-Low balance group.

While reaching targets on initial movement is, to an extent, the best indicator of dynamic balance, correctional movements, on average, allowed participants to attain and "hold" target position, in agreement with previous work[15]. Again, there was large variation in corrective movement magnitude. An interpretation of these corrective movements toward "holding" the target position would appear to represent postural sway and would contribute to greater MXE and MXE/EPE. Indeed, MXE/EPE was significantly associated with SV in the sample population and was greater in both low balance groups (EPE-Low and SV-High). Overall, this supports the assertion that greater instability (sway) while standing on one leg during the active process of stepping contributes to impaired step replacement and is ultimately indicated TMD/KMD.

Relative to the ST, one interesting conflict with above conclusions regarding step number relates to a secondary ST variable, height. Step number was lower, and TMD and MMD greater in males. In accordance with our conclusion, this would suggest some balance dysfunction in males, but none was present as LOS and SV performance was not different from females. TMD and MMD differences remained after correcting for step number (Table 1). As with our previous study[28], height has the potential to affect stepping pattern and movement/displacement per step. Presently, males were taller, and interestingly, the EPE-Low balance group, which included females, was taller. KMD, an indicator of knee motion, was not different by gender nor EPE-balance group suggesting that knee motion during stepping was similar and does not explain this height effect. However, gender-differences in TMD, but not MMD, remained after correcting for height (Table 1). Further, MMD/height tended to be greater in EPE-Low balance group. Thus, it would appear that height might independently affect movement displacement in relation to number and/or stepping rate. This apparent interaction between step number and height requires additional study towards understanding ST performance and balance assessment.

Our research question was "is there a relationship between ST movement variables and assessments of dynamic and static balance in older individuals?" Selecting a criterion measure of balance for such a study is difficult as there is no general agreement of a gold standard method[29, 30, 32]. However, concurrent validity has been established for the NeuroCom Platform system against the Berg test and gait velocity[33]. Additionally, these authors[33] reported strong reliability (ICC's >0.84). Thus, in the absence of a criterion standard, investigators rely on high test-retest reliability of methods for assessing balance. Test-retest reliability for assessing postural sway velocity in our laboratory with the Balance Master system in 60–89 year old females is very strong (ICC range 0.88–0.96;[15]). Likewise, LOS test-retest reliability with NeuroCom Platform systems has been shown to be strong in young and middle-aged adults (r's >0.8; 29–31) and very strong in older females (60–89 years of age; ICC=0.96) in our laboratory[15]. Thus, the criterion method selected for the present study was the Balance Master Platform system given the absence of an accepted gold standard for assessing balance, strong test-retest reliability, and our own experience.

Relative to ST reliability, a preliminary analysis of test-retest of its primary movement variables reported here (TMD, MMD, KMD, and step number) show excellent test-retest reliability based on moderate to very strong intraclass coefficients (0.64–0.96). Thus, given the ST reliability (reported here) and the moderate to strong association between ST variables and postural sway assessments, it would that appear the primary ST movement variables do indeed evaluate balance. Undoubtedly, this requires additional work to more fully understand the basic, valid assessment of balance, as well as relationships between ST performance and balance relative to other indicators of balance; e.g. gait velocity, fall risk, and falling.

ST variables movement TMD and movement MMD indicate deficits in dynamic balance, while ST sway index (TMD/KMD) appears indicative of postural sway during quiet standing. As with slowed movement velocity and longer reaction time during LOS testing, lower step number appears to be a compensatory attempt to improve balance performance during the ST. Both step number and height appear to contribute to differentiation of disordered balance and should be the focus of future work. Thus, the 20-sec ST appears to provide pertinent information regarding dynamic and static balance towards identifying balance deficits in otherwise healthy, community dwelling, independent living older adults.

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Conflict of interest

The authors have declared that no competing interests exist.

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