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Quantifying Effects of Age on Balance and Gait with Inertial Sensors in Community-dwelling Healthy Adults

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Abstract

Although balance and gait deteriorate as a person ages, it is unknown if all balance and gait measures change similarly across the adult age span. We developed the Instrumented Stand and Walk test (ISAW) to provide a quick quantification of key components of balance and walking: postural sway, anticipatory postural adjustments during step initiation, gait, and turning using body-worn, inertial sensors. Our aims were to characterize how different balance and gait measures change with age and to identify key age-related measures of mobility, in a wide age range of healthy, community-dwelling adults. A total of 135 healthy, community-dwelling subjects of age range 21-89 years with no history of falls were enrolled. Subjects wore inertial sensors on the wrists, ankles, sternum and lumbar area; 37 reliable and valid measures of postural sway, step initiation, gait and turning were computed. Univariate and multivariate regression analyses were performed to examine how the measures changed with age. Several distinct correlation patterns between age and ISAW measures were observed: linear deterioration, deterioration after plateau, and subtle, or no, worsening. Spatial, but not temporal, measures of gait were age-related. The strongest age correlation was found for centroidal frequency of mediolateral postural sway ($r = -0.50$, $p = 0.001$). A hierarchical regression model revealed that age was the most important predictor of mediolateral centroidal frequency, with lower sway frequencies associated with older age, independent of gender, weight, and height. Our results showed that balance and gait represent independent control systems for mobility and not all balance and gait measures deteriorate the same way with age. Postural sway during stance was more strongly related to age than any gait, gait initiation or turning measure.

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Conflict of Interest

OHSU and Dr. Horak have a significant financial interest in APDM, a company that may have a commercial interest in the results of this research and technology. This potential institutional and individual conflict has been reviewed and managed by OHSU.

Keywords

balance; gait; aging; mobility; inertial sensor

1. Introduction

Independent functional mobility is a critical aspect of high quality of life in the elderly. (Kannus, Sievanen, Palvanen, Jarvinen, & Parkkari, 2005; Muir, Berg, Chesworth, Klar, & Speechley, 2010; Verghese, Holtzer, Lipton, & Wang, 2009) Mobility is acquired early in life by mastering foundational postural and locomotive skills, and insidiously begins to deteriorate later in life, often resulting in mobility limitations and falls (Hadders-Algra, 2005). Although numerous studies have observed the effect of older age on gait or balance, age effects on both gait and balance have not been examined in the same population across the entire adult age range. Previous studies examining the effects of aging on mobility have primarily measured gait speed. (Abrahamova & Hlavacka, 2008; Alahmari, Marchetti, Sparto, Furman, & Whitney, 2014; Bohannon, 1997; Callisaya, Blizzard, Schmidt, McGinley, & Srikanth, 2008; Elble, Thomas, Higgins, & Colliver, 1991; Studenski et al., 2011; Verlinden et al., 2013) However, spatial and temporal measures of gait may not be affected by age in the same way. In addition to gait measures balance components are also crucial to consider for age-related changes in functional mobility. (Horak, 2006; S. E. Lord, Weatherall, & Rochester, 2010)

Most studies examining the effects of aging on postural sway simply measure postural sway area, rather than extracting a variety of measures that characterize standing balance, such as the frequency and velocity of postural sway. (Maurer & Peterka, 2005; Rocchi, Chiari, & Cappello, 2004; Rocchi, Chiari, Cappello, & Horak, 2006) This is the first study to quantify a wide range of mobility-related measures, including postural sway during stance, step initiation, spatial and temporal measures of gait, and turning characteristics. (Abrahamova & Hlavacka, 2008; Alahmari et al., 2014; Beavers et al., 2013; Bohannon, 1997; Bohannon & Williams Andrews, 2011; Bonnet, Mercier, & Szafrarczyk, 2013; Callisaya et al., 2008; Elble, Hughes, & Higgins, 1992; Elble et al., 1991; Samson et al., 2001; Takeshima et al., 2013; Verlinden et al., 2013; Woo, Ho, Lau, Chan, & Yuen, 1995)

A quick objective assessment of functional mobility is important to clinicians because of the growing geriatric population and desire for them to maintain mobility and independence. (Horak & Mancini, 2013; Nutt, Horak, & Bloem, 2011) Gait and balance function can be a reliable indicator for health status, quality of life and a predictor of future falls in community-dwelling elderly. (Muir et al., 2010; Verghese et al., 2009) In fact, gait speed is related to life expectancy and cognitive impairments. (Buracchio et al., 2011; Mielke et al., 2012; Studenski et al., 2011; Taekema, Gussekloo, Westendorp, de Craen, & Maier, 2012; Watson et al., 2010) However, the importance of dynamic balance measures during walking (such as step initiation, turn duration or double support time) to predict functional independence and falls is less well known. (Hamacher, Singh, Van Dieen, Heller, & Taylor, 2011; S. Lord, Galna, Verghese, et al., 2013) A better understanding of the age effects on a variety of gait and balance measures will help identify reliable markers for the diagnosis of

and therapeutic intervention for neurological diseases that alter balance and gait.(Horak & Mancini, 2013; Mancini et al., 2011; Mancini, Salarian, et al., 2012; Mancini, Zampieri, Carlson-Kuhta, Chiari, & Horak, 2009; Salarian et al., 2010; Salarian et al., 2009; Spain et al., 2012; Zampieri et al., 2010)

We developed the Instrumented Stand and Walk test (ISAW) as a short, less than one-minute test, using body-worn inertial sensors to automatically and quickly assess 1) postural sway in standing, 2) postural adjustments associated with step initiation, 3) spatiotemporal components of gait, and 4) turning.(Mancini, Salarian, et al., 2012) The sensitivity, reliability and validity of the automatic algorithms calculating the postural sway, step initiation, gait and turning measures of the ISAW have been described previously and show that specific measures can be used to detect subtle balance and gait deficits in patients with Parkinson's disease or multiple sclerosis.(Mancini, Salarian, et al., 2012; Salarian et al., 2010; Spain et al., 2012; Zampieri et al., 2010)

The aims of our present study were to quantify age-related changes with objective measures of balance and gait during standing and walking across a wider age-range than previous studies, and also to identify which of the 37 most reliable ISAW measures are most affected by age in a healthy community-dwelling cohort.

2. Methods

2.1. Participants

We recruited 149 independent community dwellers with self-reported excellent health from our laboratory database and spouses of subjects with Parkinson's disease. Data was analyzed from a total of 135 subjects (age range 21-89 yrs; mean $\pm$ SD, 57.7 $\pm$ 17.1). The inclusion criteria were as follows: a) no history of falls; b) able to stand for 30 seconds and walk for 7 meters without an assistive device; and c) no significant cognitive impairment or mood disorder that would limit ability to follow the instructions. Exclusion criteria included a) history of falls, b) neurological or musculoskeletal impairments that could affect balance or gait, c) chronic diseases such as significant vascular comorbidity, d) taking medications that could affect balance or gait, e) self-report of any mobility limitation or f) unable to consent. Data from fourteen subjects were excluded from this analysis due to unstable sensor attachments, violation of instructions or musculoskeletal abnormalities observed during examination. Before assessment, volunteers signed an informed consent form approved by the OHSU Institutional Review Board. Prior to the ISAW test, subject height (cm) and weight (kg) were recorded.

2.2. ISAW test

Postural sway, step initiation, gait and turning while walking were measured in a hospital hallway using the ISAW test protocol and algorithms of the 'Mobility Lab' system (APDM, Inc.).(Mancini, King, et al., 2012) Six, synchronized, inertial sensors (Opals) were attached to the wrists, ankles, sternum and lumbar area (L5 level) with elastic straps and recorded 9 degrees-of-freedom of motion at 128 Hz. A laptop computer presented a script with instructions for the tester to tell the subject; data were streamed to the laptop computer

during trials and ISAW measures were automatically calculated by the Mobility Lab system. Initial standing position was standardized using a template to position the subject's feet in a toe open angle of 14° with the distance between the heels of 10 cm.(Chiari, Rocchi, & Cappello, 2002; Maki, Holliday, & Fernie, 1990) Participants were instructed to stand quietly for 30s and then instructed to walk at their usual pace for 7m, turn 180° (after crossing a line on the floor) and walk back to the initial location. Subjects performed three ISAW trials and the median values were used for analysis to minimize effects of outliers.

The ISAW test includes four main subtasks: postural sway in stance, anticipatory postural adjustments (APA) during step initiation, gait, and turning. Based on the results of our previous studies and the literature. (Galna, Lord, Burn, & Rochester, 2015; S. Lord, Galna, & Rochester, 2013; Mancini et al., 2011; Mancini, Salarian, et al., 2012; Salarian et al., 2010; Spain et al., 2012; Zampieri et al., 2010), we chose from over 90 measures calculated in the ISAW test, the 37 most reliable and valid measures of balance and gait for analysis. A description of each of the 37 measures is summarized in Table 1. These measures include: 18 balance-related measures (time-domain, frequency-domain and jerkiness) derived from 30 seconds of postural sway during quiet standing, 3 measures derived from step initiation, 11 gait-related (spatial and temporal) measures derived from the 2 × 7m gait, and 5 measures derived from the 180° turn.

2.3. Statistical procedures

Univariate analyses were performed for demographic variables (age, weight, height, and gender) and the selected 37 individual measures, respectively. For each measure, mean values and standard deviation (interquartile range, if needed) were calculated in the overall sample and in each 10-year, age strata. Normality of distribution was explored using the D'Agostino-Pearson omnibus K2 normality test at 0.05 alpha level. All of the statistical analyses were performed using SPSS (v22) and statistical significance was set to 0.05.

Inter-correlations between the measures were evaluated using correlation matrix (R-matrix) based on Pearson's correlation coefficients in order to ascertain how well the selected measures could be separated statistically into gait and balance measures.

Scatter plots were used to explore correlations between age and each measure. Smoothing spline (Loess line) was used for nonparametric graphical exploration of changing patterns of measures across ages.(Jacoby, 2000) ANOVA test among 3 grouped samples by age (young adults, 20-39 years, n=30; middle-aged, 40-59 years, n=30; and older adults, above 60 years, n=75) was also used to make sure of the significance of the smoothing spline. Strength and direction of the correlations with age were measured using Pearson's product moment correlation (r), because we treated some of the measures which did not pass the normality test as if they were normally distributed, based on the central limit theorem.(Rosner, 2000) We also confirmed that the strength and direction of correlations with age were similar with nonparametric statistics as well (Spearman's rho). Partial correlation coefficients (r*), adjusting for weight and height, were also computed in the overall sample and also in separate samples for men and women to investigate potential gender differences in these relationships.(Beavers et al., 2013; Ko, Tolea, Hausdorff, & Ferrucci, 2011)

A series of hierarchical multivariable regression of age with the measures that showed strong, univariate correlations with age ($|r| \geq 0.30$, $p < 0.01$) were performed to quantify independent age-effects on these measures, after adjusting for weight, height, and gender. (Bohannon, 1997; Chiari et al., 2002; Ko et al., 2011; Samson et al., 2001) Based on the results of correlation analyses and previous reports, the entering order of predictor variable into the equation was chosen to cull away “nuisance” variance and evaluate age-effects. Weight and height were entered at the first and second steps, respectively, to account for variance in the measures attributable to individual differences in weight and height (weight ranged from 45 to 123 kg, height ranged from 152 to 203 cm). Gender was entered into the model at the third step of these analyses, and age was entered into the model at the last step to assess the unique variance in each parameter explained by age alone, after controlling for the influence of weight, height and gender. The increment in explained variance (R^2) was obtained and tested for significance at each step of the analysis.

3. Results

3.1. Overview

The breakdown of subjects by age and gender is illustrated in Figure 1. There was no difference of mean age between women (58.3 ± 16.15) and men (56.5 ± 18.91), but, on average, women weighed less (67.47 ± 12.94 versus 83.90 ± 14.425 kg; $p=0.000$) and were shorter (164.23 ± 6.244 versus 178.02 ± 9.013 cm; $p=0.000$) than men.

3.2 Independent mobility measures

Mean values of the 37 measures for 10-year age strata are reported in Appendix 1 with standard deviations for normally distributed variables and interquartile ranges for non-normally distributed variables.

A correlation matrix among all the measures revealed that turning and gait subcomponents were highly correlated with each other but not with sway or step initiation (APAs), suggesting that 1) gait, 2) postural sway and 3) step initiation represent separate domains of mobility (Fig. 2). However, characteristics of straight walking and turning 180° while walking appear to be closely related (Fig. 2). Specifically, stride velocity (measure 23 In Fig. 2) showed strong correlations with 6 other gait measures, including turning measures. Other gait domain measures strongly associated with turning measures were cadence and gait cycle time (measure 24 and 25 in Fig. 2). Not all measures of postural sway were related to other measures of postural sway; jerkiness (measures 1-3) and frequency dispersion measures (measures 17-18) of postural sway were not correlated with other sway characteristics. Similarly, trunk RoM (range of motion) during gait (measures 31-32) was not highly correlated with other gait measures, suggesting relative independence.

3.3 Correlations between age and measures of the ISAW

The Age-ISAW measure scatterplots with a smoothing spline showed three distinct patterns with advancing age: 1) Linearly deteriorating across adult life, 2) Stable performance until later in life and then deterioration and 3) Stable performance across the entire life span.

Figure 3 A-C shows representative examples of the three patterns and Figure 3D summarizes how each measure from Table 1 is affected by age.

The ISAW measures that had approximately linear deterioration across the entire age span were: RoM of the shank during gait, anteroposterior (AP) and mediolateral (ML) centroidal frequency (CF) of postural sway (Fig. 3 A) and frequency dispersion (FD) of postural sway. Most of the other measures showed a plateau with minimal change until later years, when the measure worsened abruptly: 3/5 measures in the turning domain, 10/11 measures in the gait domain (such as stride velocity Fig. 3B), and 15/18 measures in the sway domain. Measures of step initiation, such as duration of APA in Fig. 3C, had no, or minimal, worsening with age (slopes were not significantly different from zero).

The three patterns of change with age were supported by inferential statistics using one-way ANOVAs, categorized by three age groups: young adults, middle-aged adults, and older adults. For example, the mean value of postural sway centroidal (ML) in young adults was significantly greater than that of middle-aged and older adults (1.54 ± 0.31^a Hz in young, 1.17 ± 0.32^b Hz in middle aged, and 1.14 ± 0.28^c Hz in older adults; a-b, a-c, $p=0.000$, Scheffe Test). Also, the mean value of stride length in older adults was significantly shorter than that of young and middle-aged groups (89.29 ± 3.88^a in young, 88.18 ± 3.65^b in middle-aged, and 84.93 ± 5.9^c in older adults; a-c, b-c, $p=0.000$, Scheffe Test).

Statistically significant linear correlations between ISAW measures with age were found in 20 out of 37 measures, with the strongest correlation for ML centroidal frequency of sway: ($|r|>0.50$, $p<0.001$; Table 2). Other strong correlations with age ($|r|>0.30$, $p<0.01$) were found for shank RoM, length during gait, frequency distribution of sway (ML), peak shank velocity of gait, sway range (AP), and centroidal frequency of sway (AP) (in descending order; Table 2). These correlations remained significant, even after adjusting for weight and height in the overall sample and in split samples by gender (Table 2). All changes with age were consistent with deterioration of mobility.

Among the measures derived from 180° d turns (duration, # of steps, peak angular velocity, average step time, and last step time before turn; Table 2), only turn duration (related to average velocity of turning) was significantly correlated with age ($r=0.27$, $p<0.01$).

Several spatial gait measures during comfortable walking showed significant negative correlations with age (range of r , $-0.20 \sim -0.40$, $p<0.05$): stride length and stride-velocity (reflecting gait speed), RoM of the shank and trunk in the sagittal plane, and peak shank velocity. However, temporal gait measures (cadence, gait cycle time, double support, swing) were not significantly correlated with age ($p > .05$).

Thirteen out of 18 postural sway measures showed significant correlations with age (range of p -values .025-.000). The sway measure that best related to age was the centroidal frequency (ML), which had $r = -.50$, $p=.001$ overall and a partial correlation coefficient (corrected for height and weight) $r = -.43$, $P=.000$. Sway 95% ellipse area, root mean square area (RMS; AP and ML), mean velocity (ML), mean distance (AP and ML), and range (AP) also increased significantly with age (range of r , $.18 \sim .32$, $p<0.05$) and these measures did not change significantly after adjusting for weight and height. In addition, jerkiness of sway

increased with age in the anteroposterior direction ($r=.28$, $p<.01$ in jerk AP) while decreased with age in the mediolateral direction ($r=-.22$, $p<.01$ in Jerk ML; $r=-.23$, $p<.01$ in normalized jerk ML).

Among step initiation measures (anticipatory postural adjustments), only Peak ACC AP was, weakly, but significantly, correlated with age – APA were smaller with increasing age, but only in the sagittal direction ($r=-0.20$, $p<0.05$).

Height and weight had small, but significant, effects on: duration of the last step before turn, Gait cadence and gait cycle time, sway jerk ML, and step initiation peak ACC AP.

Age correlations found exclusively in women were: 95% ellipse area, RMS (AP, ML), mean distance (AP, ML), range (AP), and centroidal frequency (AP) in sway measures, stride velocity, cadence, gait cycle time, peak arm swing velocity in gait measures, and duration in turn measures. In contrast, only RoM-trunk sagittal correlated with age exclusively in men (Table 2).

3.4. Hierarchical multivariable regression analysis ISAW with age, weight, height and gender

The results of hierarchical multivariable regression of age with the ISAW measures that showed correlation coefficients with age 0.3, adjusting for height, weight, and gender, were Sway measures: range AP, centroidal frequency (AP and ML), and frequency dispersion (ML), and gait measures: stride length, RoM-shank, and peak shank velocity (summarized in Table 3). Age significantly increased the amount of explained variances in each parameter by 4.5 % to 16.5%. However, only the sway measures of centroidal frequency (ML), frequency dispersion (ML), and range (ML) were associated with age independently, whereas other measures were associated not only with age, but also with body composition and/or gender. Collectively, postural sway centroidal frequency (ML) during stance showed the strongest correlation with age and the relationship was independent of body composition and gender.

4. Discussion

In this descriptive, cross-sectional study of a community-dwelling cohort, we found that not all mobility-related measures changed in the same way with increasing age. Although most balance and gait measures showed no decline until the 6th or 7th decade, several postural sway and some spatial gait measures showed a linear deterioration across the adult age-span, starting at age 21. The ML sway centroidal frequency showed the strongest, linear correlation with age across the entire adult age range, independent of body composition (weight and height) and gender, suggesting that increasing relative amounts of low frequency sway could be a key age-related balance parameter.

We found that the strength and patterns of association between age and mobility varied widely across measures. In this study, that included young, middle-aged and old adults, most balance and gait measures from each mobility domain exhibited a trend of “deterioration only after a stable plateau” with a turning point in the 6th or 7th decade. This trend of a

minimal worsening of comfortable gait speed until approximately the age of 60 years and then prominent decay is consistent with the literature.(Bohannon, 1997; Bohannon, Andrews, & Thomas, 1996) In contrast ML sway frequency dispersion, sway centroidal frequency in both ML and AP directions, and shank RoM during gait were linearly related to age across the whole adult age span. We were surprised to find that sway frequency and stride length changed, and appeared to be deteriorating, even in the 2nd and 3rd decades of life. Different patterns of change with age are consistent with different neural control processes and/or mediators for these measures.(S. E. Lord et al., 2010)

The reason for the decrease in sway frequency with increasing age is unknown, but both biomechanical factors, such as the relative strength of hip abductors for mediolateral control of postural sway compared to strength of ankle muscles for anteroposterior sway or overall stiffness of the musculoskeletal system, as well as neural factors, such as changes in sensory integration and sensorimotor loop processing times, could play a role. For example, weakness in hip abductor muscles may result in slower left-right weight shifting while standing and increased postural response latencies may result in slower postural corrections in the elderly; both have been associated with fall risk.(Maki & McIlroy, 2006; Tang & Woollacott, 1998) The linear, gradual reduction in shank RoM, representing stride length during comfortable walking, is surprising for the younger adults and could represent the gradual decrease in energetics or effort put into “comfortable walking”.

Generally, the causes of age-related deterioration in mobility are complex and considered to be multifactorial, even in healthy, community dwelling elderly people. For example, muscle weakness, visual impairments, polyneuropathy, arthritis, depression, polypharmacy, cognitive dysfunctions, and age-related brain atrophy or white matter hyperintensities, etc. are often undiagnosed in community-dwelling older people. (Narayanan et al., 2009) Age-associations in the young and middle-aged adults could reflect more age-specific changes than that in the older adults because physiological and psychological dysfunctions in the older adults are more often modifying factors than in younger adults. Therefore, ML centroidal frequency of sway could be a key, age-related measure of the ISAW in this representative sample of even younger old, healthy, community-dwelling adults.

Our study showed that ISAW measures could be grouped statistically into three relatively independent subcomponents, gait (from turning and gait domains), balance (from postural sway domain), and step initiation. It is well known that gait speed and stride length influence other gait measures, however, their relationship with turning or balance measures has not previously been reported.(Callisaya et al., 2008; Elble et al., 1991) This study showed that gait speed and stride length were correlated not only with other gait measures, but also with measures derived from turning, but not with measures in the balance domain. In addition, arm swing velocity (°/s) and peak shank velocity (°/s), which belong to the gait domain, correlated negatively with several postural sway measures (No. 6, 7, 9, 11, 13 in Figure 2), especially in the AP direction. This finding may suggest that slowed forward locomotion (decreased arm swing or leg swing) may be to compensate for impaired balance as reflected in larger AP postural sway.

Age effects on traditional gait variables have been studied extensively, but there are few studies describing its effects on a wide range of gait measures. Reduction in gait speed and stride length with age is the most consistent finding in previous studies, consistent with the present study. However, effects of age on cadence and other temporal gait measures are still controversial.(Winter, Patla, Frank, & Walt, 1990) Age has been reported to be associated with slowing of temporal gait measures in some studies but remained unchanged in other studies.(Callisaya et al., 2008; Oberg, Karsznia, & Oberg, 1993; Samson et al., 2001) Our finding that cadence was negatively associated with age, but only in women, is consistent with the results reported by Callisaya et al. 2008.(Callisaya et al., 2008)

The present study demonstrated that most measures of sway (area, mean velocity, root mean square, range) increased with age, consistent with the results of earlier studies, although previous studies did not include young and middle aged subjects.(Abrahamova & Hlavacka, 2008; Baloh et al., 1994; Baloh, Jacobson, Enrietto, Corona, & Honrubia, 1998; Baloh, Spain, Socotch, Jacobson, & Bell, 1995; Maki & McIlroy, 1996; Overstall, Exton-Smith, Imms, & Johnson, 1977; Rogind, Lykkegaard, Bliddal, & Danneskiold-Samsoe, 2003) However, we found that frequency-domain measures of postural sway decreased remarkably with increasing age. Interestingly, age-related changes in sway jerkiness were direction-specific: jerk increased with age in the AP direction but decreased with age in the ML direction. This finding might result from a combination of increasing weakness in axial muscles for control of ML sway and stiffness from co-contraction in distal, ankle muscles for control of AP sway.(Marques et al., 2013)

A gender difference in age-related balance control is still inconclusive due to methodological heterogeneity or insufficient sample size. In this study, age associations were more commonly found in women than men. Although uneven age distribution of the subjects may be a factor, this gender-related finding supports a recent study demonstrating that older women were more unstable than older men, hypothesizing an earlier decay of proprioceptive function in women.(Riva et al., 2013)

The strength of this study is that age associations were quantified for both balance and gait measures in the same sample. Furthermore, unlike previous studies, our sample consisted of the entire adult age range, including young, middle-aged, and old adults.

There are several limitations of this study. First, cross-sectional correlations do not necessarily reflect longitudinal changes as a person ages. Second, selection criteria of subjects for this study may have reflected older subjects belonging to a relatively high level of physical performance (*e.g.*, no falls). Third, data from the older adults might have influenced the overall strength of the correlations more than that of the younger adults because of the uneven age distribution of the participants. Fourth, our ISAW test is limited in that it consists of only 14 m of walking distance. As such, we could not make accurate measurements of gait variability, which has previously been related to aging and neurological conditions. Finally, our study was designed to make quick assessments in a large number of participants; as such, we did not conduct any measurements of cognitive function nor physical fitness. It is known that cognitive ability and physical fitness can affect balance and gait measurements, so is an additional limitation in interpreting our results.

In summary, we quantified and characterized age-related changes in balance and gait across a large age range, using body-worn, inertial sensors. Our results suggest that age-related deterioration patterns of balance and gait measures may differ, and age is a strong, independent predictor of ML frequency of postural sway during standing. Moreover, normative values of ISAW grouped by 10-year age strata, which is provided in Appendix 1, may be used as reference values for future studies on balance and gait. Objective assessment of balance and gait measures, with a full appreciation of the effects of age, is important to understand the effects of neurological and musculoskeletal impairments on mobility.

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Appendix 1. Normative values of the 37 selected ISAW metrics by age per 10 years: mean $\pm$ SD in normally distributed variables and mean with interquartile range in non-normally distributed variables. (p value for one-way ANOVA test for mean difference among age groups)

1-1. Postural Sway Measures

Age (yrs)	Jerk AP (m ² /s ⁵)	Jerk ML (m ² /s ⁵)	Normalized Jerk AP	Normalized Jerk ML
20~29	0.0026(0.0018~0.0033)	0.0032(0.0016~0.0038)	1.128 $\pm$ 0.194	2.612(2.220~2.960)
30~39	0.0029(0.0018~0.0043)	0.0050(0.0017~0.0054)	1.019 $\pm$ 0.214	2.249(1.838~2.638)
40~49	0.0023(0.0017~0.0025)	0.0014(0.0008~0.0016)	1.089 $\pm$ 0.269	2.393(1.888~2.705)
50~59	0.0036(0.0025~0.0046)	0.0023(0.0012~0.0030)	1.122 $\pm$ 0.225	2.213(1.770~2.767)
60~69	0.0034(0.0023~0.0041)	0.0025(0.0012~0.0030)	1.172 $\pm$ 0.226	2.390(1.900~2.750)
70~79	0.0047(0.0030~0.0050)	0.0023(0.0013~0.0026)	1.083 $\pm$ 0.222	2.026(1.620~2.310)
80~89	0.0045(0.0038~0.0065)	0.0015(0.0011~0.0018)	0.951 $\pm$ 0.380	1.566(1.150~2.020)
Total	0.0035(0.0022~0.0042)	0.0027(0.0013~0.0029)	1.108$\pm$0.236	2.252(1.830~2.660)
CV (%)	50.00	100	21.30	27.58
p value	0.150	0.024	0.171	0.003

Notes: AP, anteroposterior; ML, mediolateral; CV, coefficient of variation m, meter; s, second; yrs, years.

Age (yrs)	Total Sway Area (m ² /s ⁵)	95%ellipse area (m ² /s ⁵)	RMS AP (m/s ²)	RMS ML (m/s ²)
20~29	0.0025(0.0016~0.0032)	0.014(0.010~0.018)	0.047(0.034~0.058)	0.016(0.013~0.018)
30~39	0.0033(0.0017~0.0037)	0.021(0.011~0.021)	0.054(0.039~0.056)	0.019(0.012~0.023)
40~49	0.0017(0.0012~0.0021)	0.012(0.008~0.017)	0.047(0.033~0.058)	0.013(0.010~0.015)
50~59	0.0026(0.0014~0.0031)	0.021(0.010~0.026)	0.054(0.043~0.063)	0.019(0.012~0.025)
60~69	0.0025(0.0017~0.0030)	0.017(0.011~0.022)	0.054(0.042~0.066)	0.017(0.014~0.021)

Age (yrs)	Total Sway Area (m ² /s ⁵)	95%ellipse area (m ² /s ⁵)	RMS AP (m/s ²)	RMS ML (m/s ²)
70~79	0.0028(0.0020~0.0031)	0.022(0.014~0.024)	0.062(0.047~0.066)	0.020(0.016~0.025)
80~89	0.0031(0.0026~0.0041)	0.036(0.021~0.065)	0.079(0.055~0.105)	0.023(0.014~0.032)
Total	0.0027(0.0016~0.0031)	0.020(0.011~0.023)	0.056(0.042~0.064)	0.018(0.014~0.021)
CV(%)	66.67	70.00	33.93	38.89
<i>p</i> value	0.357	0.006	0.004	0.022

Notes: RMS, root mean square area; AP, anteroposterior; ML, mediolateral; CV, coefficient of variation; m, meter; s, second; yrs, years.

Age (yrs)	MV AP (m/s)	MV ML (m/s)	MD AP (m ² /s ²)	MD ML (m ² /s ²)
20~29	0.099(0.059~0.142)	0.017(0.012~0.023)	0.038(0.027~0.048)	0.012(0.010~0.014)
30~39	0.122(0.076~0.150)	0.022(0.011~0.040)	0.044(0.031~0.047)	0.014(0.009~0.018)
40~49	0.079(0.041~0.099)	0.015(0.010~0.019)	0.039(0.027~0.049)	0.011(0.007~0.013)
50~59	0.102(0.059~0.129)	0.028(0.017~0.039)	0.043(0.033~0.049)	0.015(0.009~0.019)
60~69	0.110(0.068~0.130)	0.025(0.016~0.034)	0.043(0.034~0.053)	0.014(0.010~0.016)
70~79	0.109(0.074~0.142)	0.030(0.019~0.043)	0.048(0.037~0.055)	0.016(0.012~0.019)
80~89	0.173(0.105~0.245)	0.037(0.022~0.049)	0.065(0.042~0.087)	0.017(0.011~0.023)
Total	0.110(0.066~0.138)	0.025(0.014~0.034)	0.045(0.034~0.051)	0.014(0.010~0.017)
CV (%)	54.55	60.00	35.56	35.71
<i>p</i> value	0.074	0.009	0.007	0.046

Notes: MV, mean velocity; mean distance; AP, anteroposterior; ML, mediolateral; CV, coefficient of variation; m, meter; s, second; yrs, years.

Age (yrs)	S-Range AP (m ² /s ²)	S-Range ML (m ² /s ²)	S-CF AP (Hz)	S-CF ML (Hz)
20~29	0.225(0.166~0.270)	0.105(0.087~0.109)	0.71±0.10	1.55±0.28
30~39	0.270(0.220~0.296)	0.148(0.086~0.177)	0.64±0.09	1.53±0.35
40~49	0.223(0.175~0.248)	0.078(0.066~0.090)	0.66±0.16	1.30±0.26
50~59	0.280(0.221~0.338)	0.116(0.072~0.147)	0.64±0.13	1.14±0.33
60~69	0.265(0.217~0.317)	0.110(0.087~0.127)	0.61±0.12	1.21±0.27
70~79	0.329(0.255~0.361)	0.125(0.088~0.130)	0.57±0.11	1.09±0.26
80~89	0.376(0.287~0.461)	0.132(0.084~0.183)	0.57±0.20	0.88±0.21
Total	0.280(0.220~0.320)	0.117(0.083~0.130)	0.62±0.13	1.24±0.33
CV (%)	32.86	46.15	20.97	26.61
<i>p</i> value	0.000	0.053	0.028	0.000

Notes: S, Sway; CF, centroidal frequency; AP, anteroposterior; ML, mediolateral; CV, coefficient of variation; Hz, Hertz; m, meter; s, second; yrs, years.

Age (yrs)	S-FD AP	S-FD ML
20~29	0.80±0.03	0.63±0.09
30~39	0.80±0.03	0.63±0.12

Age (yrs)	S-FD AP	S-FD ML
40~49	0.80±0.04	0.67±0.04
50~59	0.80±0.04	0.71±0.09
60~69	0.81±0.04	0.70±0.07
70~79	0.81±0.03	0.71±0.06
80~89	0.79±0.04	0.74±0.06
Total	0.80±0.04	0.69±0.08
CV (%)	5.00	11.59
<i>p</i> value	0.890	0.000

Notes: S, Sway; FD, frequency dispersion; AP, anteroposterior; ML, mediolateral; CV, coefficient of variation; yrs, years.

1-2. Step Initiation Measures

Age (yrs)	Peak <u>ACC</u> AP (m/s ²)	Peak <u>ACC</u> ML (m/s ²)	Duration (s)
20~29	0.069(0.042~0.077)	0.059(0.043~0.076)	0.423(0.336~0.493)
30~39	0.066(0.038~0.088)	0.053(0.039~0.063)	0.472(0.426~0.529)
40~49	0.045(0.032~0.061)	0.046(0.034~0.058)	0.436(0.344~0.523)
50~59	0.052(0.028~0.066)	0.059(0.042~0.077)	0.455(0.408~0.528)
60~69	0.052(0.036~0.071)	0.049(0.036~0.057)	0.583(0.380~0.540)
70~79	0.053(0.042~0.062)	0.049(0.032~0.060)	0.507(0.438~0.562)
80~89	0.044(0.027~0.049)	0.040(0.031~0.043)	0.447(0.398~0.508)
Total	0.054(0.036~0.068)	0.052(0.037~0.060)	0.503(0.400~0.539)
CV (%)	50.00	40.39	63.42
<i>p</i> value	0.159	0.207	0.583

Notes: ACC, acceleration; AP, anteroposterior; ML, mediolateral; CV, coefficient of variation; m, meter; s, second; yrs, years.

1-3. Gait Measures

Age (yrs)	G-Stride Length (% of Ht)	G-Stride Velocity (% of Ht/s)	G-Cadence (step/min)	G-GCT (s)
20~29	89.5(87.9~92.7)	86.0±8.1	115.5(109.5~124.0)	1.0±0.1
30~39	89.2(86.3~91.3)	86.3±8.5	116.0(107.8~124.5)	1.0±0.1
40~49	87.9(86.4~90.1)	87.8±6.2	120.3(112.0~124.5)	1.0±0.1
50~59	88.3(86.3~91.8)	83.1±8.7	112.9(107.4~118.5)	1.1±0.1
60~69	85.9(81.6~90.3)	83.7±9.4	116.7(110.2~123.8)	1.0±0.1
70~79	84.8(80.6~89.2)	82.6±10.6	116.3(105.7~125.0)	1.0±0.1
80~89	80.5(79.2~83.1)	72.1±4.5	107.1(105.0~111.0)	1.1±0.1
Total	86.6(83.1~90.6)	83.6±9.4	115.6(109.2~122.4)	1.0±0.1
CV (%)	6.24	11.24	8.30	10.00
<i>p</i> value	0.000	0.019	0.134	0.123

Notes: G, gait; GCT, gait cycle time; CV, coefficient of variation; Ht, height; s, second; yrs, years.

Age (yrs)	G-Double Support (% of GCT)	G-Swing (% of GCT)	G-RoM-Shank (°)	G-Peak Shank Velocity (°/s)
20~29	19.5±3.6	40.2±1.8	84.8(82.4~87.2)	421.7±40.2
30~39	22.5±4.4	38.8±2.2	84.2(80.9~87.3)	441.8±45.0
40~49	20.6±2.6	39.7±1.3	83.4(81.4~85.2)	429.1±37.6
50~59	22.3±4.4	38.8±2.2	82.8(81.1~84.8)	412.3±35.3
60~69	22.4±4.7	38.8±2.3	80.4(77.6~84.5)	404.1±41.9
70~79	21.5±3.9	39.2±2.0	80.1(77.1~83.8)	408.2±45.9
80~89	24.3 ±5.8	37.8±2.9	74.9(72.8~77.7)	348.3 ±14.9
Total	21.9±4.4	39.0±2.2	81.5(78.8~85.3)	410.9±44.4
CV (%)	20.09	5.64	6.50	10.81
<i>p</i> value	0.231	0.236	0.000	0.000

Notes: G, gait; RoM-Shank, range of motion shank; CV, coefficient of variation; GCT, gait cycle time; °, degrees; %, percent; yrs, years.

Age (yrs)	G-Peak Arm Swing Velocity (°/s)	G-RoM-Trunk Sagit (°)	G-RoM-Trunk Horiz (°)
20~29	155.1±47.5	4.6±0.9	5.1±1.4
30~39	179.2±53.9	4.5±1.0	4.7±1.9
40~49	165.6±51.5	4.3±1.0	4.2±1.8
50~59	178.3±50.7	4.8±1.4	5.1±1.5
60~69	170.1±51.6	4.1±1.0	4.8±1.6
70~79	157.9±38.4	4.2±1.0	5.0±1.9
80~89	129.3±33.7	3.6±0.7	3.8±1.7
Total	166.2±48.6	4.3±1.1	4.8±1.7
CV (%)	29.24	25.58	35.42
<i>p</i> value	0.223	0.099	0.570

Notes: G, gait; RoM-Trunk Sagit, range of motion trunk in sagittal plane; RoM-Trunk Horiz, range of motion trunk in horizontal plane; AP, anteroposterior; ML, mediolateral; CV, coefficient of variation; °, degrees; s, seconds; yrs, years.

1-4. Turning Measures

Age (yrs)	T-duration (s)	T-# of steps (n)	T-Peak Angular Velocity (°/s)	T-Average Step Time (s)	T-LSTBT (s)
20~29	1.84±0.25	4.3±0.6	181.23±23.58	0.57(0.53~0.59)	0.53(0.48~0.57)
30~39	1.75±0.23	4.1±0.6	189.75±24.77	0.56(0.51~0.60)	0.53(0.50~0.56)
40~49	1.64±0.22	3.6±0.7	202.75±12.79	0.56(0.51~0.60)	0.52(0.48~0.56)
50~59	1.80±0.28	3.4±0.8	191.11±33.52	0.60(0.54~0.63)	0.54(0.53~0.58)
60~69	1.89±0.30	3.9±0.9	185.16±33.23	0.59(0.53~0.61)	0.53(0.49~0.57)
70~79	2.02±0.36	4.2±0.9	178.06±39.87	0.57(0.53~0.60)	0.53(0.49~0.58)
80~89	2.11±0.32	4.3±1.1	162.29±22.63	0.61(0.57~0.65)	0.56(0.54~0.58)
Total	1.88±0.31	3.9±0.9	184.69±32.21	0.58(0.53~0.61)	0.53(0.50~0.57)

Age (yrs)	T-duration (s)	T-# of steps (n)	T-Peak Angular Velocity (°/s)	T-Average Step Time (s)	T-LSTBT (s)
CV (%)	16.49	23.08	1.20	18.97	9.43
<i>p</i> value	0.003	0.018	0.207	0.902	0.613

Notes: T, turn; LSTBT, last step time before turn; AP, antero-posterior; ML, mediolateral; CV, coefficient of variation; #, n, number; s, seconds; °, degrees; yrs, years.

References

- Abrahamova D, Hlavacka F. Age-related changes of human balance during quiet stance. *Physiol Res*. 2008; 57(6):957–964. [PubMed: 18052683]
- Alahmari KA, Marchetti GF, Sparto PJ, Furman JM, Whitney SL. Estimating postural control with the balance rehabilitation unit: measurement consistency, accuracy, validity, and comparison with dynamic posturography. *Arch Phys Med Rehabil*. 2014; 95(1):65–73. doi: 10.1016/j.apmr.2013.09.011. [PubMed: 24076084]
- Baloh RW, Fife TD, Zwerling L, Socotch T, Jacobson K, Bell T, Beykirch K. Comparison of static and dynamic posturography in young and older normal people. *J Am Geriatr Soc*. 1994; 42(4):405–412. [PubMed: 8144826]
- Baloh RW, Jacobson KM, Enrietto JA, Corona S, Honrubia V. Balance disorders in older persons: quantification with posturography. *Otolaryngol Head Neck Surg*. 1998; 119(1):89–92. [PubMed: 9674519]
- Baloh RW, Spain S, Socotch TM, Jacobson KM, Bell T. Posturography and balance problems in older people. *J Am Geriatr Soc*. 1995; 43(6):638–644. [PubMed: 7775722]
- Beavers KM, Beavers DP, Houston DK, Harris TB, Hue TF, Koster A, Kritchevsky SB. Associations between body composition and gait-speed decline: results from the Health, Aging, and Body Composition study. *Am J Clin Nutr*. 2013; 97(3):552–560. doi: 10.3945/ajcn.112.047860. [PubMed: 23364001]
- Bohannon RW. Comfortable and maximum walking speed of adults aged 20–79 years: reference values and determinants. *Age Ageing*. 1997; 26(1):15–19.
- Bohannon RW, Andrews AW, Thomas MW. Walking speed: reference values and correlates for older adults. *J Orthop Sports Phys Ther*. 1996; 24(2):86–90. doi: 10.2519/jospt.1996.24.2.86. [PubMed: 8832471]
- Bohannon RW, Williams Andrews A. Normal walking speed: a descriptive meta-analysis. *Physiotherapy*. 2011; 97(3):182–189. doi: 10.1016/j.physio.2010.12.004. [PubMed: 21820535]
- Bonnet CT, Mercier M, Szaflarczyk S. Impaired mediolateral postural control at the ankle in healthy, middle-aged adults. *J Mot Behav*. 2013; 45(4):333–342. doi: 10.1080/00222895.2013.799056. [PubMed: 23781920]
- Buracchio TJ, Mattek NC, Dodge HH, Hayes TL, Pavel M, Howieson DB, Kaye JA. Executive function predicts risk of falls in older adults without balance impairment. *BMC Geriatr*. 2011; 11:74. doi: 10.1186/1471-2318-11-74. [PubMed: 22070602]
- Callisaya ML, Blizzard L, Schmidt MD, McGinley JL, Srikanth VK. Sex modifies the relationship between age and gait: a population-based study of older adults. *J Gerontol A Biol Sci Med Sci*. 2008; 63(2):165–170. [PubMed: 18314452]
- Chiari L, Rocchi L, Cappello A. Stabilometric parameters are affected by anthropometry and foot placement. *Clin Biomech (Bristol, Avon)*. 2002; 17(9-10):666–677.
- Elble RJ, Hughes L, Higgins C. The syndrome of senile gait. *J Neurol*. 1992; 239(2):71–75. [PubMed: 1552306]
- Elble RJ, Thomas SS, Higgins C, Colliver J. Stride-dependent changes in gait of older people. *J Neurol*. 1991; 238(1):1–5. [PubMed: 2030366]

- Galna B, Lord S, Burn DJ, Rochester L. Progression of gait dysfunction in incident Parkinson's disease: impact of medication and phenotype. *Mov Disord*. 2015; 30(3):359–367. doi: 10.1002/mds.26110. [PubMed: 25546558]
- Hadders-Algra M. Development of postural control during the first 18 months of life. *Neural Plast*. 2005; 12(2-3):99–108. discussion 263–172. doi: 10.1155/NP.2005.99. [PubMed: 16097478]
- Hamacher D, Singh NB, Van Dieen JH, Heller MO, Taylor WR. Kinematic measures for assessing gait stability in elderly individuals: a systematic review. *J R Soc Interface*. 2011; 8(65):1682–1698. doi: 10.1098/rsif.2011.0416. [PubMed: 21880615]
- Horak FB. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age Ageing*. 2006; 35(Suppl 2):ii7–ii11. doi: 10.1093/ageing/afl077. [PubMed: 16926210]
- Horak FB, Mancini M. Objective biomarkers of balance and gait for Parkinson's disease using body-worn sensors. *Mov Disord*. 2013; 28(11):1544–1551. doi: 10.1002/mds.25684. [PubMed: 24132842]
- Jacoby WG. Loess: a nonparametric, graphical tool for depicting relationships between variables. *Electoral Studies*. 2000; 19:577–613.
- Kannus P, Sievanen H, Palvanen M, Jarvinen T, Parkkari J. Prevention of falls and consequent injuries in elderly people. *Lancet*. 2005; 366(9500):1885–1893. doi: 10.1016/S0140-6736(05)67604-0. [PubMed: 16310556]
- Ko SU, Tolea MI, Hausdorff JM, Ferrucci L. Sex-specific differences in gait patterns of healthy older adults: results from the Baltimore Longitudinal Study of Aging. *J Biomech*. 2011; 44(10):1974–1979. doi: 10.1016/j.jbiomech.2011.05.005. [PubMed: 21601861]
- Lord SE, Weatherall M, Rochester L. Community ambulation in older adults: which internal characteristics are important? *Arch Phys Med Rehabil*. 2010; 91(3):378–383. doi: 10.1016/j.apmr.2009.11.008. [PubMed: 20298827]
- Lord S, Galna B, Rochester L. Moving forward on gait measurement: toward a more refined approach. *Mov Disord*. 2013; 28(11):1534–1543. doi: 10.1002/mds.25545. [PubMed: 24132841]
- Lord S, Galna B, Verghese J, Coleman S, Burn D, Rochester L. Independent domains of gait in older adults and associated motor and nonmotor attributes: validation of a factor analysis approach. *J Gerontol A Biol Sci Med Sci*. 2013; 68(7):820–827. doi: 10.1093/gerona/gls255. [PubMed: 23250001]
- Maki BE, Holliday PJ, Fernie GR. Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. *J Am Geriatr Soc*. 1990; 38(1):1–9. [PubMed: 2295764]
- Maki BE, McIlroy WE. Postural control in the older adult. *Clin Geriatr Med*. 1996; 12(4):635–658. [PubMed: 8890108]
- Maki BE, McIlroy WE. Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. *Age Ageing*. 2006; 35(Suppl 2):ii12–ii18. doi: 10.1093/ageing/afl078. [PubMed: 16926197]
- Mancini M, Horak FB, Zampieri C, Carlson-Kuhta P, Nutt JG, Chiari L. Trunk accelerometry reveals postural instability in untreated Parkinson's disease. *Parkinsonism Relat Disord*. 2011; 17(7):557–562. doi: 10.1016/j.parkreldis.2011.05.010. [PubMed: 21641263]
- Mancini M, King L, Salarian A, Holmstrom L, McNames J, Horak FB. Mobility Lab to Assess Balance and Gait with Synchronized Body-worn Sensors. *J Bioengineer & Biomedical Sci*. 2012; S1 doi: 10.4172/2155-9538.s1-007.
- Mancini M, Salarian A, Carlson-Kuhta P, Zampieri C, King L, Chiari L, Horak FB. ISway: a sensitive, valid and reliable measure of postural control. *J Neuroeng Rehabil*. 2012; 9:59. doi: 10.1186/1743-0003-9-59. [PubMed: 22913719]
- Mancini M, Zampieri C, Carlson-Kuhta P, Chiari L, Horak FB. Anticipatory postural adjustments prior to step initiation are hypometric in untreated Parkinson's disease: an accelerometer-based approach. *Eur J Neurol*. 2009; 16(9):1028–1034. doi: 10.1111/j.1468-1331.2009.02641.x. [PubMed: 19473350]
- Marques NR, LaRoche DP, Hallal CZ, Crozara LF, Morcelli MH, Karuka AH, Goncalves M. Association between energy cost of walking, muscle activation, and biomechanical parameters in

- older female fallers and non-fallers. *Clin Biomech* (Bristol, Avon). 2013; 28(3):330–336. doi: 10.1016/j.clinbiomech.2013.01.004.
- Maurer C, Peterka RJ. A new interpretation of spontaneous sway measures based on a simple model of human postural control. *J Neurophysiol*. 2005; 93(1):189–200. doi: 10.1152/jn.00221.2004. [PubMed: 15331614]
- Mielke MM, Roberts RO, Savica R, Cha R, Drubach DI, Christianson T, Petersen RC. Assessing the Temporal Relationship Between Cognition and Gait: Slow Gait Predicts Cognitive Decline in the Mayo Clinic Study of Aging. *J Gerontol A Biol Sci Med Sci*. 2012 doi: 10.1093/gerona/gls256.
- Muir SW, Berg K, Chesworth B, Klar N, Speechley M. Quantifying the magnitude of risk for balance impairment on falls in community-dwelling older adults: a systematic review and meta-analysis. *J Clin Epidemiol*. 2010; 63(4):389–406. doi: 10.1016/j.jclinepi.2009.06.010. [PubMed: 19744824]
- Narayanan MR, Scalzi ME, Redmond SJ, Lord SR, Celler BG, Lovell NH. Evaluation of functional deficits and falls risk in the elderly--methods for preventing falls. *Conf Proc IEEE Eng Med Biol Soc*. 2009; 2009:6179–6182. doi: 10.1109/IEMBS.2009.5334506. [PubMed: 19964895]
- Nutt JG, Horak FB, Bloem BR. Milestones in gait, balance, and falling. *Mov Disord*. 2011; 26(6): 1166–1174. doi: 10.1002/mds.23588. [PubMed: 21626560]
- Oberg T, Karsznia A, Oberg K. Basic gait parameters: reference data for normal subjects, 10-79 years of age. *J Rehabil Res Dev*. 1993; 30(2):210–223. [PubMed: 8035350]
- Overstall PW, Exton-Smith AN, Imms FJ, Johnson AL. Falls in the elderly related to postural imbalance. *Br Med J*. 1977; 1(6056):261–264. [PubMed: 837061]
- Riva D, Mamo C, Fani M, Saccavino P, Rocca F, Momente M, Fratta M. Single stance stability and proprioceptive control in older adults living at home: gender and age differences. *J Aging Res*. 2013; 2013:561695. doi: 10.1155/2013/561695. [PubMed: 23984068]
- Rocchi L, Chiari L, Cappello A. Feature selection of stabilometric parameters based on principal component analysis. *Med Biol Eng Comput*. 2004; 42(1):71–79. [PubMed: 14977225]
- Rocchi L, Chiari L, Cappello A, Horak FB. Identification of distinct characteristics of postural sway in Parkinson's disease: a feature selection procedure based on principal component analysis. *Neurosci Lett*. 2006; 394(2):140–145. doi: 10.1016/j.neulet.2005.10.020. [PubMed: 16269212]
- Rogind H, Lykkegaard JJ, Bliddal H, Danneskiold-Samsøe B. Postural sway in normal subjects aged 20-70 years. *Clin Physiol Funct Imaging*. 2003; 23(3):171–176. [PubMed: 12752561]
- Rosner, B. *Fundamentals of Biostatistics*. 5th ed.. Duxbury; Pacific Grove, CA: 2000.
- Salarian A, Horak FB, Zampieri C, Carlson-Kuhta P, Nutt JG, Aminian K. iTUG, a sensitive and reliable measure of mobility. *IEEE Trans Neural Syst Rehabil Eng*. 2010; 18(3):303–310. doi: 10.1109/TNSRE.2010.2047606. [PubMed: 20388604]
- Salarian A, Zampieri C, Horak FB, Carlson-Kuhta P, Nutt JG, Aminian K. Analyzing 180 degrees turns using an inertial system reveals early signs of progression of Parkinson's disease. *Conf Proc IEEE Eng Med Biol Soc*. 2009; 2009:224–227. doi: 10.1109/IEMBS.2009.5333970. [PubMed: 19964471]
- Samson MM, Crowe A, de Vreede PL, Dessens JA, Duursma SA, Verhaar HJ. Differences in gait parameters at a preferred walking speed in healthy subjects due to age, height and body weight. *Aging (Milano)*. 2001; 13(1):16–21. [PubMed: 11292147]
- Spain RI, St George RJ, Salarian A, Mancini M, Wagner JM, Horak FB, Bourdette D. Body-worn motion sensors detect balance and gait deficits in people with multiple sclerosis who have normal walking speed. *Gait Posture*. 2012; 35(4):573–578. doi: 10.1016/j.gaitpost.2011.11.026. [PubMed: 22277368]
- Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, Guralnik J. Gait speed and survival in older adults. *JAMA*. 2011; 305(1):50–58. doi: 10.1001/jama.2010.1923. [PubMed: 21205966]
- Taekema DG, Gussekloo J, Westendorp RG, de Craen AJ, Maier AB. Predicting survival in oldest old people. *Am J Med*. 2012; 125(12):1188–1194. e1181. doi: 10.1016/j.amjmed.2012.01.034. [PubMed: 23017181]
- Takeshima N, Islam MM, Rogers ME, Rogers NL, Sengoku N, Koizumi D, Naruse A. Effects of nordic walking compared to conventional walking and band-based resistance exercise on fitness in older adults. *J Sports Sci Med*. 2013; 12(3):422–430. [PubMed: 24149147]

- Tang PF, Woollacott MH. Inefficient postural responses to unexpected slips during walking in older adults. *J Gerontol A Biol Sci Med Sci*. 1998; 53(6):M471–480. [PubMed: 9823752]
- Verghese J, Holtzer R, Lipton RB, Wang C. Quantitative gait markers and incident fall risk in older adults. *J Gerontol A Biol Sci Med Sci*. 2009; 64(8):896–901. doi: 10.1093/gerona/glp033. [PubMed: 19349593]
- Verlinden VJ, van der Geest JN, Hoogendam YY, Hofman A, Breteler MM, Ikram MA. Gait patterns in a community-dwelling population aged 50 years and older. *Gait Posture*. 2013; 37(4):500–505. doi: 10.1016/j.gaitpost.2012.09.005. [PubMed: 23018028]
- Watson NL, Rosano C, Boudreau RM, Simonsick EM, Ferrucci L, Sutton-Tyrrell K, Health, A. B. C. Study. Executive function, memory, and gait speed decline in well-functioning older adults. *J Gerontol A Biol Sci Med Sci*. 2010; 65(10):1093–1100. doi: 10.1093/gerona/glp111. [PubMed: 20581339]
- Winter DA, Patla AE, Frank JS, Walt SE. Biomechanical walking pattern changes in the fit and healthy elderly. *Phys Ther*. 1990; 70(6):340–347. [PubMed: 2345777]
- Woo J, Ho SC, Lau J, Chan SG, Yuen YK. Age-associated gait changes in the elderly: pathological or physiological? *Neuroepidemiology*. 1995; 14(2):65–71. [PubMed: 7891816]
- Zampieri C, Salarian A, Carlson-Kuhta P, Aminian K, Nutt JG, Horak FB. The instrumented timed up and go test: potential outcome measure for disease modifying therapies in Parkinson's disease. *J Neurol Neurosurg Psychiatry*. 2010; 81(2):171–176. doi: 10.1136/jnnp.2009.173740. [PubMed: 19726406]

Highlights

1. Our cross-sectional study showed that balance and gait represent independent control systems for mobility.
2. Not all balance and gait measures deteriorate the same way in aging.
3. Postural sway in stance was more strongly related to age than gait initiation, gait or turning.

Figure 1.
Age-distribution of subjects by gender.

Figure 2.

Visualization of the covariance structure across the ISAW measures (numbered below). Blue indicates positive and red indicates negative correlation. Higher color saturation indicates higher correlation. The gait and turning measures correlate with each other but not with the postural sway measures.

Measures associated with each number for SWAY: 1. Jerk (AP), 2. Jerk (ML), 3. Normalized Jerk (AP), 4. Normalized Jerk (ML), 5. Total Sway Area, 6. 95%ellipse Area, 7. RMS (AP), 8. RMS (ML), 9. MV (AP), 10. MV (ML), 11. MD (AP), 12. MD (ML), 13. Range (AP), 14. Range (ML), 15. CF (AP), 16. CF (ML), 17. FD (AP), 18. FD (ML); **STEP INITIATION (APA):** 19. Peak ACC AP, 20. Peak ACC ML, 21. Duration; **GAIT:** 22. Stride-Length, 23. Stride Velocity, 24. Cadence, 25. Gait Cycle Time, 26. Double Support, 27. Swing, 28. RoM-Shank, 29. Peak Shank Velocity, 30. Peak Arm Swing Velocity, 31. RoM-Trunk Sagit, 32. RoM-Trunk Horiz; and **TURNING:** 33. Duration, 34. Number of Steps, 35. Peak Angular Velocity, 36. Average Step Time, 37. Last Step Time Before Turn. Measures defined in Table 1.

Figure 3.

Examples of 3 types of age-related changes in ISAW measures scatter plots with smoothing spline relations. A. Centroidal frequency ML of sway deteriorates linearly (“linear deterioration”), while B. Stride-velocity declines more rapidly at old age than young and middle age (“decline after plateau”) and C. Anticipatory postural adjustment(APA) duration shows stable performance across entire age range (no worsening). D. Schematic summary of the types of age-related changes for each metric in Table 1 (number for each metric). Black line, linear regression equation; Dashed line, 95% CI; Red and blue line, Non-parametric Loess line; ML, mediolateral; APA (anticipatory postural adjustment).

Table 1

Brief description of the 37 most reliable and valid measures selected from the Instrumented Stand and Walk (ISAW) test.

Measure	#	Units	Definition
Sway			
<i>Jerk (AP, ML)</i>	1,2	m^2/s^5	Smoothness of sway from time derivative of acceleration.
<i>Normalized Jerk (AP, ML)</i>	3,4	AD	Normalized Jerk (normalized to range of acceleration excursion and duration)
<i>Total Sway Area</i>	5	m^2/s^5	Sway area, computed as the area included in the ACC per unit of time
<i>95%ellipse Area</i>	6	m^2/s^5	Area of the 95% confidence ellipse
<i>RMS (AP, ML)</i>	7,8	m/s^2	Amount of sway, from root mean square (<u>RMS</u>) of ACC time series
<i>MV (AP, ML)</i>	9, 10	m/s	Mean velocity (<u>MV</u>)
<i>MD (AP, ML)</i>	11,12	m^2/s^2	Mean distance (<u>MD</u>) from center of ACC trajectory
<i>Range (AP, ML)</i>	13, 14	m^2/s^2	Range acceleration
<i>CF (AP, ML)</i>	15, 16	Hz	Frequency of sway from centroidal frequency (<u>CF</u>) of power spectrum
<i>FD (AP, ML)</i>	17, 18	AD	Frequency dispersion (<u>FD</u>)
Step Initiation (APA's)			
<i>Peak <u>ACC</u> AP</i>	19	m/s^2	Peak <u>forward</u> trunk acceleration from baseline
<i>Peak <u>ACC</u> ML</i>	20	m/s^2	Peak lateral trunk acceleration from baseline
<i>Duration</i>	21	s	Time from <u>anticipatory postural adjustment</u> APA onset to end
Gait			
<i>Stride Length</i>	22	$\%h$	Distance between two consecutive foot-falls at the moments of initial contacts. Averaged for left and right side.
<i>Stride Velocity</i>	23	$\%h/s$	Walking speed. Averaged of the right and left sides.
<i>Cadence</i>	24	steps/min	Stepping rate
<i>GCT</i>	25	s	Duration of a complete gait cycle.
<i>Double Support</i>	26	% GCT	Percentage of a gait cycle that both feet are on the ground.
<i>Swing</i>	27	% GCT	Percentage of a gait cycle that either foot is off the ground.
<i>RoM-Shank</i>	28	$^{\circ}$	Range-of-motion (<u>ROM</u>) of shanks; averaged of the left and right sides.
<i>Peak Shank Velocity</i>	29	$^{\circ}/s$	Peak (95%) angular velocity of shanks. Average of the left and right sides.
<i>Peak Arm Swing Velocity</i>	30	$^{\circ}/s$	Peak (95%) angular velocity of arms. Average of the left and right sides.
<i>RoM-Trunk Sagit</i>	31		Range-of-motion of trunk in sagittal plane.
<i>RoM-Trunk Horiz</i>	32	$^{\circ}$	Range-of-motion of trunk in horizontal plane.
Turning			
<i>Duration</i>	33	s	Duration of 180° turn.
<i># of Steps</i>	34	<u>number</u>	Number of steps during the turn
<i>Peak Angular Velocity</i>	35	$^{\circ}/s$	Peak angular velocity of trunk during turning.
<i>Average Step <u>Time</u></i>	36	s	Average step duration during turning.
<i>LSTBT</i>	37	s	The last step duration right before turn.

Notes: ACC, acceleration; AD, adimensional AP, anteroposterior; GCT, gait cycle time; Horiz, horizontal; Hz, Hertz; LSTBT, last step time before turn; ML, mediolateral; m, meters; min, minute; #, number; s, seconds; Sagit, sagittal.

Table 2

The ISAW measures with simple and partial correlation coefficients to age, controlling for weight and height (as needed ^{*}).

Measures (unit)	All subjects				By gender			
	Overall (n=135)		Overall (n=135)		Women (n=88)		Men (n=47)	
	<i>r</i>	<i>p</i> value	<i>r</i> [*]	<i>p</i> [*] value	<i>r</i> [*]	<i>p</i> [*] value	<i>r</i> [*]	<i>p</i> [*] value
<i>Sway</i>								
<i>Jerk AP (m²/s⁵)</i>	0.28	0.001 [*]	0.29	0.001 [*]	0.23	0.038 [*]	0.52	0.000[*]
<i>Jerk ML (m²/s⁵)</i>	-0.22	0.009 [*]	-0.15	0.090	-0.14	0.202	-0.15	0.322
<i>Normalized Jerk AP</i>	0.00	0.986	0.05	0.550	-0.11	0.314	0.24	0.114
<i>Normalized Jerk ML</i>	-0.23	0.006 [*]	-0.18	0.037 [*]	-0.21	0.053	-0.14	0.356
<i>Total Sway Area (m²/s⁵)</i>	0.00	0.986	0.05	0.549	0.17	0.122	-0.10	0.535
<i>95%ellipse Area (m²/s⁵)</i>	0.19	0.025 [*]	0.21	0.017 [*]	0.30	0.005[*]	0.10	0.532
<i>RMS AP (m/s²)</i>	0.27	0.002 [*]	0.25	0.004 [*]	0.36	0.001[*]	0.08	0.590
<i>RMS ML (m/s²)</i>	0.18	0.034 [*]	0.20	0.021 [*]	0.23	0.031 [*]	0.19	0.219
<i>MV AP (m/s)</i>	0.11	0.226	0.10	0.265	0.19	0.082	-0.03	0.846
<i>MV ML (m/s)</i>	0.28	0.001 [*]	0.28	0.001 [*]	0.30	0.005[*]	0.30	0.046[*]
<i>MD AP (m²/s²)</i>	0.24	0.006 [*]	0.21	0.014 [*]	0.33	0.002[*]	0.05	0.734
<i>MD ML (m²/s²)</i>	0.21	0.014 [*]	0.21	0.014 [*]	0.22	0.043 [*]	0.25	0.101
<i>Range AP (m²/s²)</i>	0.32	0.000[*]	0.30	0.000[*]	0.36	0.001[*]	0.24	0.120
<i>Range ML (m²/s²)</i>	0.00	0.985	0.05	0.540	0.14	0.202	-0.03	0.828
<i>CF AP (Hz)</i>	-0.30	0.000[*]	-0.22	0.010 [*]	-0.33	0.002[*]	-0.10	0.531
<i>CF ML (Hz)</i>	-0.50	0.000[*]	-0.43	0.000[*]	-0.34	0.001[*]	-0.58	0.000[*]
<i>FD AP</i>	0.01	0.917	0.03	0.717	0.14	0.209	-0.15	0.342
<i>FD ML</i>	0.38	0.000[*]	0.33	0.000[*]	0.33	0.002[*]	0.36	0.016[*]
<i>Step Initiation (APAs)</i>								
<i>Peak ACC AP (m/s²)</i>	-0.20	0.022 [*]	-0.17	0.057	-0.13	0.248	-0.23	0.129
<i>Peak ACC ML (m/s²)</i>	-0.14	0.098	-0.08	0.372	0.04	0.719	-0.21	0.160
<i>Duration (s)</i>	0.10	0.251	0.07	0.438	0.11	0.333	0.03	0.864
<i>GAIT</i>								
<i>Stride-Length (% h)</i>	-0.38	0.000[*]	-0.37	0.000[*]	-0.41	0.000[*]	-0.37	0.014[*]
<i>Stride-Velocity (% h/s)</i>	-0.24	0.005 [*]	-0.23	0.008 [*]	-0.39	0.000[*]	-0.27	0.069
<i>Cadence (steps/min)</i>	-0.07	0.442	-0.19	0.027 [*]	-0.22	0.044 [*]	-0.10	0.502

Measures (unit)	All subjects				By gender			
	Overall (n=135)		Overall (n=135)		Women (n=88)		Men (n=47)	
	<i>r</i>	<i>p</i> value	<i>r</i> *	<i>p</i> * value	<i>r</i> *	<i>p</i> * value	<i>r</i> *	<i>p</i> * value
<i>Gait Cycle Time (s)</i>	0.07	0.413	0.20	0.019 *	0.23	0.031 *	0.10	0.495
<i>Double Support (% GCT)</i>	0.15	0.084	0.03	0.730	0.07	0.536	−0.02	0.907
<i>Swing (%)</i>	−0.15	0.085	−0.03	0.736	−0.07	0.546	0.02	0.917
<i>RoM-Shank (°)</i>	−0.40	0.000 *	−0.35	0.000 *	−0.43	0.000 *	−0.30	0.044 *
<i>Peak Shank Velocity (°/s)</i>	−0.33	0.000 *	−0.43	0.000 *	−0.47	0.000 *	−0.38	0.010 *
<i>Peak Arm Swing Velocity (°/s)</i>	−0.08	0.342	−0.15	0.082	−0.21	0.049 *	0.02	0.888
<i>RoM-Trunk Sagit (°)</i>	−0.20	0.022 *	−0.23	0.009 *	−0.15	0.161	−0.36	0.014 *
<i>RoM-Trunk Horiz (°)</i>	−0.04	0.664	0.01	0.918	0.01	0.895	−0.01	0.963
Turn								
<i>Duration (s/180°)</i>	0.27	0.001 *	0.26	0.003 *	0.24	0.024 *	0.25	0.100
<i># of Steps (number)</i>	0.00	0.982	−0.02	0.784	−0.05	0.658	−0.04	0.810
<i>Peak Angular Velocity, (°/s)</i>	−0.12	0.143	−0.09	0.311	−0.06	0.591	−0.10	0.524
<i>Average Step Time, (s)</i>	0.06	0.479	0.09	0.288	0.13	0.240	0.02	0.898
<i>LSTBT, (s)</i>	0.07	0.454	0.18	0.040 *	0.18	0.108	0.12	0.441

Notes: *r**, partial correlation coefficients adjusting for weight and height

Bolded results show significant p-values after correction for multiple comparisons.

Definitions in Table 1.

*
p<0.05

Table 3

Summary of the series of hierarchical multiple regression analyses predicting variables of the ISAW test that showed strong correlations ($r = 0.3$) with age ($n=135$).

Criterion variables	Standardized Beta Coefficients				R^2	Change in R^2	df	F Change	p-value
	Weight (kg)	Height (cm)	Gender (versus women)	Age (yrs)					
<i>Range AP</i>	1	-0.009			0.000	0.000	1/133	0.010	0.921
	2	0.056	-0.125		0.012	0.011	1/132	1.535	0.218
	3	0.053	-0.133	0.014	0.012	0.000	1/131	0.013	0.910
	4	-0.031	0.015	-0.027	0.321	0.090	1/130	13.039	0.000
<i>CF AP</i>	1	0.114			0.013	0.013	1/133	1.752	0.188
	2	-0.097	0.407		0.134	0.121	1/132	18.473	0.000
	3	-0.114	0.361	0.081	0.138	0.003	1/131	0.518	0.473
	4	-0.054	0.256	0.110	0.183	0.045	1/130	7.208	0.008
<i>CF ML</i>	1	-0.087			0.008	0.008	1/133	1.021	0.314
	2	-0.273	0.359		0.102	0.095	1/132	13.895	0.000
	3	-0.256	0.405	-0.082	0.106	0.003	1/131	0.507	0.478
	4	-0.142	0.204	-0.027	-0.436	0.166	1/130	29.580	0.000
<i>FD ML</i>	1	0.139			0.019	0.019	1/133	2.619	0.108
	2	0.243	-0.201		0.049	0.030	1/132	4.116	0.044
	3	0.242	-0.204	0.005	0.049	0.000	1/131	0.002	0.968
	4	0.150	-0.043	-0.039	0.350	0.156	1/130	16.482	0.000
<i>Stride Length</i>	1	-0.325			0.106	0.106	1/133	15.741	0.000
	2	-0.391	0.126		0.118	0.012	1/132	1.749	0.188
	3	-0.427	0.033	0.166	0.132	0.014	1/131	2.150	0.145
	4	-0.330	-0.137	0.213	0.251	0.120	1/130	20.784	0.000
<i>RoM-Shank</i>	1	-0.273			0.075	0.075	1/133	10.727	0.001
	2	-0.375	0.197		0.103	0.028	1/132	4.183	0.043
	3	-0.413	0.099	0.176	0.119	0.016	1/131	2.365	0.127
	4	-0.315	-0.074	0.223	0.241	0.122	1/130	20.935	0.000

Criterion variables	Standardized Beta Coefficients				R^2	Change in R^2	df	F Change	p-value
	Weight (kg)	Height (cm)	Gender (versus women)	Age (yrs)					
<i>Peak Shank Velocity</i>	1	-0.271			0.073	0.073	1/133	10.522	0.001
	2	-0.135	-0.261		0.123	0.050	1/132	7.529	0.007
	3	-0.124	-0.232	-0.053	0.125	0.001	1/131	0.214	0.644
	4	-0.011	-0.432	0.002	0.289	0.164	1/130	29.951	0.000

Notes: Variables were regressed on weight, height, gender, and age. Each predictor variable was entered into the model at a separate step, and the increment in explained variance (*i.e.*, change in R^2) was tested for significance. Standardized beta coefficients are given for predictors in the model at each step. R^2 is the variance explained by the entire regression model at that particular step in the analysis. The degrees of freedom, F ratios, and p values are associated with the change in R^2 . Significant standardized beta coefficients are listed in bold-faced. Definitions in Table 1.