



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 ($r = -0.50, p \leq 0.001$). 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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1. Introduction

Independent functional mobility is a critical aspect of high quality of life in the elderly (Kannus et al., 2005; Muir et al., 2010; Verghese et al., 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 and Hlavacka, 2008; Alahmari et al., 2014; Bohannon, 1997; Callisaya et al., 2008; Elble et al., 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; Lord et al., 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 and Peterka, 2005; Rocchi et al., 2004; Rocchi et al., 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 and Hlavacka, 2008; Alahmari et al., 2014; Beavers et al., 2013; Bohannon, 1997; Bohannon and Williams Andrews, 2011; Bonnet et al., 2013; Callisaya et al., 2008; Elble et al., 1992; Elble et al., 1991; Samson et al., 2001; Takeshima et al., 2013; Verlinden et al., 2013; Woo et al., 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 and Mancini, 2013; Nutt et al., 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).

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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 et al., 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 et al., 2011; Lord et al., 2013a, 2013b). 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 and Mancini, 2013; Mancini et al., 2011; Mancini et al., 2012a, 2012b; Mancini et al., 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 et al., 2012a). 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 et al., 2012a; 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 ± 17.1). The inclusion criteria were as follows: a) no history of falls; b) able to stand for 30 s and walk for 7 m 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 et al., 2012a). 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 et al., 2002; Maki et al., 1990).

Participants were instructed to stand quietly for 30s and then instructed to walk at their usual pace for 7 m, 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 et al., 2015; Lord et al., 2013a, 2013b; Mancini et al., 2011; Mancini et al., 2012a, 2012b; 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 s of postural sway during quiet standing, 3 measures derived from step initiation, 11 gait-related (spatial and temporal) measures derived from the 2×7 m 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 et al., 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.

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