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Trunk-acceleration based assessment of gait parameters in older persons: A comparison of reliability and validity of four inverted pendulum based estimations

Agnes Zijlstra [a,*], Wiebren Zijlstra [a,b]

[a] Center for Human Movement Sciences, University of Groningen, University Medical Center Groningen, Groningen, The Netherlands
[b] Institute of Movement and Sport Gerontology, German Sport University Cologne, Cologne, Germany

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ABSTRACT

Inverted pendulum (IP) models of human walking allow for wearable motion-sensor based estimations of spatio-temporal gait parameters during unconstrained walking in daily-life conditions. At present it is unclear to what extent different IP based estimations yield different results, and reliability and validity have not been investigated in older persons without a specific medical condition. The aim of this study was to compare reliability and validity of four different IP based estimations of mean step length in independent-living older persons. Participants were assessed twice and walked at different speeds while wearing a tri-axial accelerometer at the lower back. For all step-length estimators, test–retest intra-class correlations approached or were above 0.90. Intra-class correlations with reference step length were above 0.92 with a mean error of 0.0 cm when (1) multiplying the estimated center-of-mass displacement during a step by an individual correction factor in a simple IP model, or (2) adding an individual constant for bipedal stance displacement to the estimated displacement during single stance in a 2-phase IP model. When applying generic corrections or constants in all subjects (i.e. multiplication by 1.25, or adding 75% of foot length), correlations were above 0.75 with a mean error of respectively 2.0 and 1.2 cm. Although the results indicate that an individual adjustment of the IP models provides better estimations of mean step length, the ease of a generic adjustment can be favored when merely evaluating intra-individual differences. Further studies should determine the validity of these IP based estimations for assessing gait in daily life.

1. Introduction

Aging is often accompanied by a decrease in balance and mobility performance, which frequently leads to fear of falling and reduced physical activity. As a consequence, a further decline in physical health can occur associated with a higher risk of falls and hospitalization [1]. To be able to assist in maintaining healthy independent mobility and living, objective methods for early identification and monitoring of older persons at risk of (further) developing mobility problems are needed. A feasible option is the use of wearable movement sensors to assess daily physical activity and gait.

When using a single 3D-accelerometer at the lower back near the body's center of mass (CoM), periods of walking can be detected with high sensitivity [2,3], however it is unclear whether gait parameters can be properly assessed from daily-life data. Accurate identification of step cycles and fair estimation of temporal gait parameters have already been demonstrated for straight-line walking in standardized conditions [4–8]. Assuming an inverted pendulum (IP) type of walking, lower-back accelerations can be used to estimate step length [5]. For walking in standardized conditions, fair estimations of step length have been demonstrated in children, young adults, neurological populations and patients with lower-limb amputations [5,9–12], but not yet in older persons without a specific medical condition. Moreover, different IP models can be used for estimating step length, and it is yet unclear which approach provides the most reliable and valid results. The aim of the present study is therefore to evaluate reliability and agreement with reference step length of several lower-back acceleration based estimations of step length in independent-living older adults.

* Corresponding author at: Center for Human Movement Sciences, University of Groningen, University Medical Center Groningen, P.O. Box 196, 9700 AD Groningen, The Netherlands. Tel.: +31 050 363 2710; fax: +31 050 363 3150.
E-mail address: a.zijlstra@umcg.nl (A. Zijlstra).

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2. Methods

2.1. Subjects and protocol

The 20 independent-living older adults (aged 69–80 years) included in the study were recruited from sports groups for seniors and an old people's home. Exclusion criteria were the use of walking aids, and self-report of neurological or musculoskeletal conditions that significantly affect mobility. Two subjects reported one fall incident in the past year, five reported hearing problems, and none of the subjects reported problems with their vision. In Table 1 further characteristics are given, including Timed Up and Go (TUG) test scores and ability to perform (household) activities of daily living (GARS). The local ethical committee approved the study and all participants provided informed consent.

At two test sessions (t1, t2) on different days, subjects walked along a 30 m straight-line path in an indoor public hallway while wearing low-heeled shoes. Subjects were instructed not to talk while walking. Twelve trials of walking 30 m at self-selected speeds were performed, first 2 × 2 trials at preferred speed, then 2 trials at respectively fast, preferred and slow speed, and finally 2 trials at preferred speed while simultaneously performing an auditive version of the Stroop task [13]. Subjects were allowed to rest between trials whenever necessary.

2.2. Data acquisition

Accelerations of the lower trunk were measured by a wireless, hybrid sensor (DynaPort Hybrid, McRoberts, The Hague, NL) containing a tri-axial accelerometer (range $\pm 2 \times g$) and gyroscopes. The hybrid sensor (size 87 mm × 45 mm × 14 mm, weight 74 g) was inserted in an elastic belt and centered on the lower back at the level of vertebrae L2–L4. Data were measured at a sampling frequency of 100 Hz and stored on a micro secure digital (SD) memory card that was inserted in the hybrid sensor. The sensor was operated using a remote-control application (McRoberts, The Hague, NL) on a netbook and a wireless connection. The start and end of the middle 25 m of each 30-m walk were indicated by lines on the floor. When the subject passed these lines, a research assistant pushed a button to set markers in the sensor data which were subsequently used to select gait data and calculate gait speed.

2.3. Data analysis

In order to analyze steady-state walking, parameters were calculated for the middle 25 m of a walk, thus gait initiation and termination were excluded from the data analysis (cf. [14]). To obtain step times, the instants of heel-strike were determined from the forward lower-trunk accelerations [5,6]. Mean step length of a trial was calculated by multiplying mean step time and mean walking speed (25 m/duration), and was used as the reference step length (Xstep). The ratio between step length and step frequency (L/F ratio) was also calculated. Four estimators of mean step length were obtained using variations of the IP model of walking.

- Estimator 1a (Xstep^{IP}) – Mean step length was estimated using a simple IP model as described in Zijlstra and Hof [5,15]: step length = 1.25 * $2\sqrt{(2lh - h^2)}$. Forward displacement of the CoM was estimated during the total step period from the amplitude of its change in vertical position (h) and leg length (l) as pendulum length. Step length was subsequently obtained by applying a *generic correction factor* of 1.25 to correct for underestimation. The vertical amplitude (h) was determined as the difference between highest and lowest position of the CoM in the total step cycle. CoM positions were obtained by double integration of the vertical lower-trunk accelerations. Leg length was measured as the distance from the ground to the greater trochanter with shoes on.
- Estimator 1b ($\text{Xstep}^{\text{IPi}}$) – Mean step length was estimated similar as for estimator 1a, except for applying an *individual correction factor (Fi)*: step length = Fi * $2\sqrt{(2lh - h^2)}$. For each walking trial the reference step length (Xstep) was divided by the mean forward CoM displacement (mean for all steps of, $2\sqrt{(2lh - h^2)}$) and the average for all 12 × 2 trials was taken as the subject's individual correction factor (Fi).
- Estimator 2a ($\text{Xstep}^{\text{IP2}}$) – Mean step length was estimated using a two-stage IP model that was proposed by Gonzalez et al. [11] to eliminate the need for a correction factor: step length $= C + 2\sqrt{(2l_b h_b - h_b^2)}$. First, forward displacement of the CoM was estimated during the single-stance phase of the step from the CoM vertical amplitude (h_b) during single stance, and leg length (l) −10 cm as pendulum length (l_b) which approximates the distance from the lateral malleolus to the greater trochanter. Second, a *predetermined constant (C)* of 75% of foot length was added for double-stance CoM displacement, approximated as the displacement of the center of pressure in the foot.
- Estimator 2b ($\text{Xstep}^{\text{IP2i}}$) – Mean step length was estimated similar as for estimator 2a, except for applying an *individual constant (Ci)*: step length $= \text{Ci} + 2\sqrt{(2l_b h_b - h_b^2)}$. For each walking trial the difference between the reference step length (Xstep) and the mean single-stance forward CoM displacement (mean for all steps of $2\sqrt{(2l_b h_b - h_b^2)}$) was calculated, and the average for all 12 × 2 trials was taken as the subject's individual constant (Ci).

Table 1
Characteristics of the independent-living older adults.

N = 20 (17♀)	Mean	SD	Min–Max
Age [years]	73.8	3.0	69–80
Body mass[a] [kg]	75.7	10.8	59–102
Height[a] [m]	1.656	0.062	1.52–1.79
Leg length[a,b] [m]	0.939	0.047	0.85–1.04
PASE (0–**360**)	192.8	58.6	95–293
Short FES-I (**7**–24)	8.0	1.4	7–12
GARS (**18**–72)	19.4	2.4	18–25
TUG test[c] [s]	9.00	1.07	7.2–11.1

PASE: Physical Activity Scale for the Elderly (adapted Dutch version) [18]; Short FES-I: Short Falls Efficacy Scale-International [19]; GARS: Groningen Activities Restriction Scale [20]; TUG: Timed Up and Go [21]. Best score is indicated in bold.
[a] Body mass, height and leg length were measured with shoes on.
[b] Distance between the ground and the greater trochanter.
[c] Average score for 4 repetitions over 2 test sessions performed with the instruction 'walk brisk but safely'.

2.4. Statistical analysis

After Kolmogorov–Smirnov tests approved normal distribution of data, parametric tests were applied. Paired samples t-tests were used to determine systematic differences between test sessions. Relative reliabilities were expressed as single measures, two-way random, type absolute agreement intra-class correlation coefficients ($\text{ICC}_{2,1}$) and associated 95% confidence intervals (CI). To ascertain homoscedasticity absolute, individual between-test differences were plotted against the individual means of both test sessions. Relative agreement between IP based estimated and reference step length was expressed as single measures, two-way mixed, type consistency intra-class correlation coefficients ($\text{ICC}_{3,1}$) and associated 95% CI. Reliability or agreement was considered 'high' when ICCs were above 0.90 and 'good' when ICCs were between 0.75 and 0.90. Bland–Altman plots [16] were generated, and as a measure for absolute agreement the mean difference (MD) between estimated and reference step length was taken. Limits of agreement (LOA) were calculated as 2 times the standard deviation (SD) of differences to estimate the interval within which 95% of differences would lie.

3. Results

Three subjects did not follow instructions for in total 4 walking trials, therefore data of 8 trials (4 × 2 sessions) out of 480 were excluded from the analyses. No significant differences in reference step length (Xstep) existed between the first and second trial of a (speed) condition (paired samples t-tests, $\alpha < 0.05$, 18–20 cases) and $\text{ICCs}_{2,1}$ were all above 0.90. Table 2 therefore gives the walking parameters averaged for the first and second trial. Results for CoM vertical amplitude and forward displacement are given in Table 3.

Individual correction factors ranged from 1.09 to 1.35 (mean 1.217 ± 0.074), predetermined constants of 75% of foot length ranged from 0.18 to 0.21 (mean 0.19 ± 0.01), and individual constants from 0.12 to 0.23 (mean 0.180 ± 0.030). Calculation based on only the walking trials at preferred speed led to similar means for individual correction factor (1.216 ± 0.075) and individual constant (0.182 ± 0.032) in comparison to calculation based on all trials. When calculating individual correction factors or constants separately for the two test sessions, test–retest $\text{ICCs}_{2,1}$ were respectively 0.878 (95% CI 0.634–0.955) and 0.757 (95% CI 0.287–0.912). The group mean differed between test sessions for individual factor (1.23 ± 0.07 versus 1.21 ± 0.08, $p = 0.011$) as well as individual constant (0.19 ± 0.03 versus 0.17 ± 0.03, $p = 0.002$).

3.1. Reliability of IP based estimations of step length

A significant difference between test sessions was found in the averaged $\text{Xstep}^{\text{IPi}}$ for the first two trials at preferred speed (t1 0.683 m ± 0.061 versus t2 0.677 m ± 0.055, $p < 0.05$, 37 cases), whereas a near significant difference was found for Xstep^{IP} (t1 0.704 m ± 0.077 versus t2 0.698 m ± 0.075, $p = 0.05$, 37 cases). The overall ICC (236 cases) was high for Xstep^{IP} ($\text{ICC}_{2,1} = 0.952$, 95% CI 0.938–0.962) and $\text{Xstep}^{\text{IPi}}$ ($\text{ICC}_{2,1} = 0.932$, 95% CI 0.912–0.947), as well as for $\text{Xstep}^{\text{IP2}}$ ($\text{ICC}_{2,1} = 0.958$, 95% CI 0.946–0.967) and $\text{Xstep}^{\text{IP2i}}$