Reliability and clinical correlates of 3D-accelerometry based gait analysis outcomes according to age and fall-risk

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ABSTRACT

Purpose: To investigate the reliability of a 3D-accelerometry based gait analysis, and its correlates with clinical status and fall-risk.

Methods: Forty elderly subjects presenting with increased fall-risk (OFR), 41 elderly controls (OC) and 40 young controls (aged 80.6 ± 5.4, 79.1 ± 4.9 and 21.6 ± 1.4 years respectively) underwent three gait evaluations (two assessors in random order) each containing two walks of 18 m with a DynaPort MiniMod accelerometer on the pelvis. Intra- and inter-observer reliability of gait speed, step-time asymmetry, mediolateral and craniocaudal step and stride regularity were determined by ICC and CV of standard error of measurement (CVSEM). Relationships with cognition (MMSE), dependency, grip strength, muscle endurance, and fall-risk (fall-history, timed-get-up-and-go and Tinetti-test) were analysed in elderly participants.

Results: Reliability for single walk was low (ICC < 0.70, 11% < CVSEM < 23%), except for mediolateral step regularity (0.70 < ICC < 0.80) and gait speed (ICC > 0.80, CVSEM < 7%), but high (ICC > 0.70, 4% < CVSEM < 20%) when based on the mean of two walks; except for step-time asymmetry (42% < CVSEM < 77%). Compared to OC, OFR showed significantly (p < 0.05) slower gait speed, and worse step and stride regularity. Gait speed, step-time asymmetry, step and stride regularity related significantly (p < 0.05) with several functional outcomes. Besides gait speed (1.158 m/s, 78% sensitivity and 78% specificity), none of the gait features showed sufficient discriminative capacity according to fall-risk.

Conclusions: In all participants together, 3D-accelerometry based gait speed and regularity showed high reliability when based on two walks of 18 m. Relationships with functional characteristics support the validity of gait variability features in elderly persons. More fundamental and prospective research is necessary to clarify their clinical value.

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1. Introduction

Ageing is accompanied by decreasing physiological functions, among which are muscle atrophy and weakness, defined as sarcopenia. Various unfavourable elements including life style (e.g. low physical activity level, malnutrition) and clinical conditions (e.g. morbidity, polypharmacy, surgery, immobilization) can accelerate the process [1], and many elderly persons develop a complex geriatric profile defined as frailty [2]. Accordingly, elderly persons are continuously exposed to multi-factorial processes, increasingly affecting mobility, balance and ambulation. One of the consequences is an increased risk for falls and subsequent exacerbation of morbidity and mortality.

Most assessment tools used for fall-risk screening in elderly persons are based on visual observation and/or timing of physical performance [3,4]. Although their predictive value is undeniable, cut-off-values for clinical use merely correspond with clearly visible instability or reduced ambulation. To detect more subtle gait disturbances, instrumented assessment has been developed, for example, gait analysis using force plates, gyroscopes [5], tri-axial (3D) accelerometers attached on the lower trunk, or combinations of the above [6]. Several features obtained by 3D-accelerometry characterise the gait pattern such as walking speed,
step and stride time, step-time asymmetry, and auto-correlations of mediolateral or craniocaudal acceleration periods among steps or strides [7].

Significant differences in gait pattern based on 3D-accelerometry have been reported in subjects presenting different clinical conditions [8] or gait abnormalities [7]. However, for most 3D-accelerometry based features, cut-off values for clinical fall-risk assessment in elderly patients are lacking. Also, the reliability is mainly reported for basic gait parameters in healthy persons [9–11] and remains unclear for gait variability features, especially in elderly patients with increased fall-risk.

The aim of this study was to investigate the reliability of 3D-accelerometry acquired parameters to measure gait variability in a diverse sample of young and elderly persons. Also, the clinical correlates and the discriminative capacity of these outcomes in the context of fall-risk assessment were explored.

2. Methods

2.1. Participants

121 persons participated: 40 elderly subjects presenting with increased fall-risk (OFR, aged ≥65 years); 41 elderly controls (OC, aged ≥65 years); and 40 young controls (YC, aged 18–30 years). Elderly participants were recruited from the geriatric department of a university hospital, from the research department’s database of elderly volunteers and from seniors’ organisations. YC were recruited among staff and students of the university. Subjects were screened for exclusion criteria by interview and excluded when cognitively deficient (Mini-Mental-State Examination (MMSE)-score < 23/30) [12] or when unable to understand/perform the test instructions/procedures; when unable to walk 20 m without assistance; when presenting with Parkinson’s disease or cerebro-vascular accidents with locomotor disability. Co-morbidity was not an exclusion criterion per se, except for acute/uncontrolled conditions. The study protocol was approved by the local ethical committee and all participants gave written informed consent.

2.2. Measurements

2.2.1. Dependency

Dependency for basic activities of daily life (bADL) was assessed using a 6-item scale as described by Katz et al. [13], and complemented by orientation in time and place. Each item was scored from one (completely independent or no problem in orientation) to four (completely dependent or completely disoriented). Dependancy for instrumental ADL (IADL) was evaluated using a 9-item questionnaire following Lawton et al. [14]. Each item was scored from one (completely dependent) to three (completely independent).  

2.2.2. Muscle performance

Grip strength and endurance of the dominant hand were measured using the Martin Vibrometer (Elmed inc., Addison, USA) as described previously [15–17]. The subject was asked to squeeze the large bulb of the Vibrometer as hard as possible; the highest of three attempts represented maximal grip strength (in kPa). Afterwards, the subjects were instructed to squeeze the bulb as hard as possible and to maintain this maximal pressure; the time (in seconds) during which grip strength dropped to 50% of its maximum was recorded as fatigue resistance [17]. Grip work was calculated by multiplying the fatigue resistance by 75% of the maximal grip strength [18], and expressed per kg body mass as described previously [18,19].

2.2.3. Increased fall risk

Increased fall-risk was documented by three different criteria: a recent (previous 6 months) history of fall(s) and/or timed get-up-and-go test ≥15 s and/or Tinetti-test score ≤24/28 [3,4]; which are respectively a self-reported scale, a single-task and a multiple-task performance test [20]. A fall was defined as unintentionally coming to the floor while standing or walking 

2.2.4. Gait analysis procedure and data processing

A 3-D piezoresistive accelerometer (Dynaport GaitTest acquisition software, MIRAI, Amsterdam, The Netherlands; acquisition rate 100 Hz) was used to capture the ground reaction force along three axes (anteroposterior, mediolateral, and craniocaudal) at the 6th metatarsal head. Informed consent was obtained from each participant. Twenty-two sensors were placed bilaterally at the 6th metatarsal head as described previously [21,22]. Accelerometry data were processed after masking for test-condition (test–test) and group assignment via GaitWeb. Foot contacts were determined as described by Zijlstra et al. [21]. In order to avoid bias due to the start and stop phases of the walk, the first and last two steps were excluded from all analyses. Gait speed was calculated as described previously by Senden et al. [22], and step-time asymmetry as:

\[
\text{step-time asymmetry} = \frac{\text{mean step time left leg} - \text{mean step time right leg}}{\text{mean step times both legs}}
\]

Medio-lateral and vertical step-and-stride-regularity were computed as unbiased autocorrelation coefficients according to Moe-Nilssen and Helbostad [7].

2.3. Statistical analysis

Data were analysed using PASW-Statistics 17.0.2 (SPSS Inc., Illinois, USA). Intra Class Correlation (ICC) coefficients (model 2.1) were computed and interpreted [17,23] as ICC ≥ 0.90 = excellent; 0.80 ≤ ICC < 0.90 = very good; 0.70 ≤ ICC < 0.80 = good; 0.60 ≤ ICC < 0.70 = fair; ICC < 0.60 = poor. Differences between groups and between walks were assessed by ANOVA (respectively one-way and repeated-measures) or Student’s t-test (respectively unpaired and paired comparisons). Since step-time asymmetry was not normally distributed in OC and YC (Kolmogorov-Smirnov Goodness of Fit p < 0.05) Wilcoxon-signed-rank and Kruskal-Wallis tests were used. The standard error of measurement (SEM = Sd / √ N) was removed and the data were loaded on a computer. For each participant three gait tests (consisting of 2 walks, including positioning of the accelerometer, instructing the participant and uploading of the data) were randomly assigned to two out of three assessors, from whom one assessor tested the participant twice (in a random order). At each repositioning, the height of the accelerometer relative to the floor was measured to the nearest 0.01 m using a stadimeter.

Raw accelerometer data were uploaded on a local computer using Dynaport GaitTest acquisition software (MiRA1.9.4.b2; Miroberts, The Hague, The Netherlands) and signals corresponding to each walk were identified. Accelerometry data were processed after masking for test-condition (test–test) and group assignment via GaitWeb. Foot contacts were determined as described by Zijlstra et al. [21]. In order to avoid bias due to the start and stop phases of the walk, the first and last two steps were excluded from all analyses. Gait speed was calculated as described previously by Senden et al. [22], and step-time asymmetry as:

\[
\text{step-time asymmetry} = \frac{\text{mean step time left leg} - \text{mean step time right leg}}{\text{mean step times both legs}}
\]

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ORF</th>
<th>OC</th>
<th>YC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>80.6 ± 5.4</td>
<td>79.1 ± 4.9</td>
<td>21.6 ± 1.4</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>161.8 ± 12.1</td>
<td>164.6 ± 7.7</td>
<td>175.3 ± 8.0</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>66.9 ± 15.0</td>
<td>69.7 ± 11.4</td>
<td>68.7 ± 13.4</td>
</tr>
<tr>
<td>MMSE (scores 0–30)</td>
<td>27.4 ± 2.2</td>
<td>28.3 ± 1.4</td>
<td>30.0 ± 0.0</td>
</tr>
<tr>
<td>Grip strength (kPa)</td>
<td>48.9 ± 17.8</td>
<td>58.7 ± 17.5</td>
<td>96.9 ± 23.5</td>
</tr>
<tr>
<td>Grip work/kg body mass</td>
<td>31.5 ± 20.6</td>
<td>38.1 ± 17.2</td>
<td>51.0 ± 19.4</td>
</tr>
<tr>
<td>bADL-Dependence (scores 8–32)</td>
<td>8.7 ± 0.9</td>
<td>8.3 ± 0.6</td>
<td>8.0 ± 0.0</td>
</tr>
<tr>
<td>iADL-Dependence (scores 9–27)</td>
<td>22.6 ± 2.0</td>
<td>24.4 ± 2.0</td>
<td>27.0 ± 0.0</td>
</tr>
<tr>
<td>Co-morbidity (number)</td>
<td>3.0 ± 1.4</td>
<td>2.9 ± 1.3</td>
<td>0.3 ± 0.5</td>
</tr>
<tr>
<td>Medication use (number)</td>
<td>4.7 ± 2.9</td>
<td>4.0 ± 3.0</td>
<td>0.2 ± 0.5</td>
</tr>
<tr>
<td>Get-up-and-go (s)</td>
<td>15.6 ± 10.8</td>
<td>8.8 ± 1.7</td>
<td>5.8 ± 1.2</td>
</tr>
<tr>
<td>Tinetti-balance (scores 0–16)</td>
<td>13.6 ± 1.8</td>
<td>15.3 ± 0.8</td>
<td>16.0 ± 0.0</td>
</tr>
<tr>
<td>Tinetti-gait (scores 0–12)</td>
<td>10.7 ± 1.4</td>
<td>11.9 ± 0.4</td>
<td>12.0 ± 0.0</td>
</tr>
<tr>
<td>Fail(s) in history (yes/no)</td>
<td>30/10</td>
<td>0/41</td>
<td>0/40</td>
</tr>
</tbody>
</table>

| Mean ± SD or number, ORF = old fall risk, OC = old controls, YC = young controls. |

**1** Significantly different from YC (One-way ANOVA with Bonferroni post-hoc test p < 0.05).
No significant differences were found for accelerometer-to-floor height between gait tests (respectively 1.018 ± 0.054 m, 1.016 ± 0.056 m and 1.016 ± 0.055 m; repeated measures ANOVA F = 1.067, p = 0.346) and excellent intra- and inter-observer reproducibility was found (ICC = 0.96, CVSEM = 1.07% and ICC = 0.94, CVSEM = 1.35% respectively). Intra- and inter-observer reliability for gait speed, step-time asymmetry and step- and stride-regularity are shown in Table 2 (results for OFR, EC and YC separately available as Supplementary files). ICC, mean differences (95% CI) as well as SEM and CVSEM were calculated for a single walk (walk-1, i.e. 18 m ahead) as well as for the mean of two walks (mean of walk-1 and -2, i.e. 18 m ahead and 18 m return). Gait speed showed very good to excellent reliability for both single and mean of two walks (ICC > 0.80 and CVSEM < 7%); however, small but significant (p < 0.05) improvement in gait speed was found between subsequent walks (except for the YC separately). For the remaining outcomes, reliability for a single walk was generally fair to poor (ICC > 0.70, 11% < CVSEM < 23%), except for mediolateral step regularity (0.70 < ICC < 0.80). Gait parameters based on the mean of two walks showed better CVSEM-values and good to excellent reliability (ICC > 0.70); except for craniocaudal step and stride regularity in the OC (intra-observer reliability ICC = 0.49 and 0.59 respectively, inter-observer reliability ICC = 0.67) and mediolateral step and stride regularity in the YC (inter-observer reliability ICC = 0.62 and 0.63 respectively). For step-time asymmetry, high CVSEM-values (range 42%–77%) were found.

Differences for gait characteristics (mean of two walks) were analysed according to age and fall-risk (see Fig. 1A–D). Compared to YC, OFR showed slower walk speed, worse craniocaudal step and stride regularity, and worse mediolateral step and stride regularity (all p < 0.05). Compared to YC, OFR and YC showed slower gait speed and worse mediolateral step regularity; OFR showed worse mediolateral stride regularity; and, remarkably, OFC showed better craniocaudal step and stride regularity (all p < 0.05). No significant differences were found for step-time asymmetry (see Fig. 1B).

In order to identify the clinical correlates of 3D-accelerometry outcomes, partial correlation coefficients (controlling for age) were computed for all elderly participants (N = 81, see Table 3). Faster gait speed was significantly (p < 0.01) related to better scores on cognitive and all physical performance outcomes as well as to more independence. Higher asymmetry in step-time was significantly related to worse scores for bADL dependency (p < 0.01), muscle endurance (p < 0.05) and Tinetti-gait test (p < 0.01). Higher craniocaudal step and stride regularity were significantly related to better scores for dependency in bADL (p < 0.01), grip strength (p < 0.05 for step regularity, borderline for stride regularity), get-up-and-go test (p < 0.05 for stride regularity, borderline for step regularity) and for both balance and gait subscale of the Tinetti-test (all p < 0.01, except p < 0.05 for stride regularity). Better mediolateral step and stride regularity were significantly (p < 0.01) related to higher scores on the Tinetti-balance test.

In a stepwise logistic regression analysis, gait speed was the only significant factor related to fall-risk in the elderly participants (overall correct classification increased from 51% to 77%, b-coefficient = 5.72, p < 0.01). The capacity of gait analysis outcomes to discriminate OFR from OC is shown in Fig. 2. As can be seen, all outcomes showed low discriminative capacity, except for gait speed showing 78% sensitivity and 78% specificity when using 1.158 m/s as cut-off value (AUC = 0.83).

4. Discussion

We investigated the reliability of a 3D-accelerometry based gait analysis in a diverse sample of young and elderly persons. Our results showed that overall, the reliability of gait features was better when based on the mean of two walks (18 m ahead and 18 m return) compared to a single walk (18 m ahead). In fact, reliability for single walk was fair to poor (ICC < 0.70, 11% < CVSEM < 23%), except for mediolateral step regularity and gait speed. Since most outcome parameters based on the mean of two walks showed better CVSEM-values and good to excellent reliability (ICC > 0.70), it is advisable that for repeated measures, as well as in clinical decision making, gait analysis should contain at least two walks. The mean test–retest differences as well as the SEM-values we report here can be used as a reference for the interpretation of gait-parameter changes in longitudinal studies. However, for step-time asymmetry, high CVSEM-values (range 42%–77%) were found, thus questioning its value in clinical assessment. Between each gait analysis, the accelerometer was removed and repositioned at the pelvis. It cannot be excluded that differences in positioning of the accelerometer introduced supplementary bias to the reliability. However, accelerometer-
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To our knowledge, this is one of the first large studies investigating the reliability of gait features obtained by 3D-accelerometry involving elderly subjects \( (N = 81) \) with different levels of fall-risk. In fact, other investigators using 3D-accelerometry reported reliability of acceleration measurements and/or primary spatio-temporal gait characteristics (step length, step duration) in young healthy subjects \[10,11\]. The ICC-values we report here for gait speed are similar to those reported by Hartmann et al. \[9\] and Senden et al. \[22\] in a smaller sample \( (N = 23 \text{ and } N = 24) \) of elderly \( (\text{aged } 73 \pm 4 \text{ and } 21-60 \text{ years respectively}) \) using the same measurement system and analogous walking distance as in our study; as well as similar to the results of Allet et al. \[24\] obtained in diabetic patients instrumented with a gyroscope while walking over various surfaces. Senden et al. \[22\] also reported problems with the intra- and inter-observer reliability of step-time asymmetry; however, in their report no specific ICC-values were given for this parameter \( (\text{respectively ICC between } 0.51-0.79 \text{ and } 0.01-0.35 \text{ for intra- and inter-observer}) \) and were based on single walks only.

We found significantly \( (p < 0.05) \) slower gait speed and gait regularity in OFR compared to EC. However, except for gait speed, none of the gait features showed sufficient discriminative capacity to correctly classify our elderly participants according to fall-risk. ROC-curve analysis revealed 1.158 m/s as a useful cut-off value for gait speed in order to discriminate OFR from OC \( (78\% \text{ sensitivity and } 78\% \text{ specificity}, \text{AUC } = 0.83) \). This cut-off value corresponds well with the mean gait speed for subjects with low fall risk \( (1.16 \pm 0.15 \text{ m/s}) \) as reported by Menz et al. \[25\], but is higher.

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**Fig. 1.** Gait characteristics according to age and fall-risk. Figures represent boxplots for (A) gait-speed \( (\text{m/s}) \), (B) step time asymmetry \( (%) \), and (C) craniocaudal and (D) mediolateral step \( (\text{white boxes}) \) and stride \( (\text{grey boxes}) \) regularity \( (\text{correlation coefficient}) \) stratified by young controls \( (\text{YC}, N = 40) \), old controls \( (\text{OC}, N = 41) \) and elderly with increased fall risk \( (\text{OFR}, N = 40) \). Compared to YC, OFR showed slower gait-speed, worse craniocaudal step and stride regularity, and worse mediolateral step and stride regularity. Compared to YC, OFR and OC showed slower gait-speed, OC showed better craniocaudal step and stride regularity. OFR and OC showed worse mediolateral step regularity and OFR showed worse mediolateral stride regularity. All contrasts \( p < 0.05 \) (one-way ANOVA with Bonferroni post-hoc test). No significant difference between groups for step time asymmetry \( (\text{Kruskall–Wallis test } p > 0.05) \).
compared to the threshold used by Lauretani et al. [26] for identifying gait problems (0.80 m/s). It has been shown that gait features can differ according to walking distance [27], and these contrast can be explained by the fact that Lauretani et al. performed gait analysis over a much shorter distance (4 m) compared to our study (18 m) and that of Menz et al. (20 m). Our results are in contrast with the high sensitivity and specificity reported by Tura et al. [28] in identifying abnormal walking patterns in transfemoral amputees based on gait regularity. The fact that gait regularity showed poor discriminative capacity might be related to the criteria we used in this study to

**Table 3**

Clinical correlates of 3D-accelerometry in elderly persons (N=81).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gait speed</th>
<th>Step time asymmetry</th>
<th>Step regularity</th>
<th>Stride regularity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC</td>
<td>ML</td>
<td>CC</td>
<td>ML</td>
</tr>
<tr>
<td>Co-morbidity</td>
<td>-0.08</td>
<td>0.11</td>
<td>-0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>Medication use</td>
<td>-0.11</td>
<td>0.11</td>
<td>-0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>MMSE</td>
<td>0.33(p&lt;0.05)</td>
<td>-0.17</td>
<td>0.19</td>
<td>-0.16</td>
</tr>
<tr>
<td>6ADL Dependency</td>
<td>-0.40(p&lt;0.01)</td>
<td>0.29(p&lt;0.01)</td>
<td>-0.32(p&lt;0.01)</td>
<td>0.04</td>
</tr>
<tr>
<td>iADL Dependency</td>
<td>0.29(p&lt;0.01)</td>
<td>0.05(p&lt;0.01)</td>
<td>0.16</td>
<td>-0.03</td>
</tr>
<tr>
<td>Grip strength</td>
<td>0.40(p&lt;0.01)</td>
<td>-0.11</td>
<td>0.23(p&lt;0.01)</td>
<td>-0.01</td>
</tr>
<tr>
<td>Grip work/kg body weight</td>
<td>0.35(p&lt;0.01)</td>
<td>-0.22(p&lt;0.01)</td>
<td>0.14</td>
<td>0.07</td>
</tr>
<tr>
<td>Get-up-and-go</td>
<td>-0.53(p&lt;0.01)</td>
<td>0.14</td>
<td>-0.21</td>
<td>0.09</td>
</tr>
<tr>
<td>Tinetti-balance</td>
<td>0.44(p&lt;0.01)</td>
<td>-0.15</td>
<td>0.35(p&lt;0.01)</td>
<td>-0.35(p&lt;0.01)</td>
</tr>
<tr>
<td>Tinetti gait</td>
<td>0.51(p&lt;0.01)</td>
<td>-0.34(p&lt;0.01)</td>
<td>0.54(p&lt;0.01)</td>
<td>-0.09</td>
</tr>
</tbody>
</table>

Partial correlation coefficients (controlling for age).

\(p < 0.05\).

\(p < 0.01\).

Fig. 2. Discriminative value of 3D-accelerometry according to fall-risk. Lines represent ROC-curves indicating capacity to distinguish elderly presenting increased fall-risk (N = 40) from elderly controls (N = 41) for (A) gait-speed (AUC = 0.83), mediolateral stride regularity (AUC = 0.68), craniocaudal step and stride regularity (respectively AUC = 0.72 and AUC = 0.71); (B) step time asymmetry (AUC = 0.54) and mediolateral step regularity (AUC = 0.68).
allocate participants to the OFR group. It cannot be excluded that elderly subjects classified as OC showed 'hidden' gait abnormalities expressed as low step or stride regularity. Also, the fact that OC subjects showed significantly (p < 0.05) better cranio-caudal step and stride regularity compared to YC suggests cautious interpretation in the clinical context, especially since one cannot discriminate between OFR and OC based on gait regularity. More fundamental research aimed at identifying the underlying mechanisms of changes in gait regularity as well as large prospective studies investigating the predictive value are necessary to clarify their clinical importance.

Clinical correlates of 3D-accelerometry outcomes were explored in all elderly participants (N = 81). As expected, faster gait speed was significantly (p < 0.01) related to better physical performance and independency. The negative relation between gait speed and cognitive functioning (p < 0.01) in our study corresponds to the recent findings of Gillain et al. [29], who reported slower gait speed in patients with mild cognitive impairment (MCI). In our study, elderly subjects presenting severe cognitive deficit (MMSE-score ≤ 23/30) were excluded, but subjects were not actively screened for MCI (often subjects with MMSE-scores between 28 and 24). Also, several significant relationships of functional outcomes with step-time asymmetry and step or stride regularity were found. Mediolateral step and stride regularity were only related to Tinetti-balance (p < 0.01), whereas cranio-caudal step regularity correlated significantly with grip strength (p < 0.05), Tinetti-balance and Tinetti-gait (both p < 0.01); and cranio-caudal stride regularity with Get-up-and-go, Tinetti-balance (both p < 0.05) and Tinetti-gait (p < 0.01). This might indicate that cranio-caudal and mediolateral step and stride regularity provide different information and could be complementary in the clinical gait assessment of elderly persons.

Interestingly, higher step-time asymmetry was significantly (p < 0.05) related to worse muscle endurance. Also Helbostad et al. [30] showed that muscle fatigue significantly affected gait in elderly persons. Possibly, evaluation over longer distances might improve the appearance of fatigue-related changes in the gait pattern. Finally, higher dependency for BADL was significantly (p < 0.01) related to worse step-time asymmetry and cranio-caudal step and stride regularity. For iADL, however, no significant relationships were found, which might be due to less frequent iADL deficits observed in our participants.

Our study has some limitations and our results may have been biased due to the criteria used for fall-risk assignment. Several outliers were observed in Fig. 18 and C1 in the YC- and OC-groups may have presented a hidden gait abnormality - which did not become apparent on the clinical evaluation, but visible when considering instrumented gait analysis. In order to limit possible cross contamination of the elderly control group and subjects presenting increased fall-risk, all elderly participants were carefully screened using three different criteria consisting of one self-reported scale, one single-task and one multiple-task performance tests. Moreover, 63% of the OFR-subjects showed get-up-and-go-values ≤ 15 s. Therefore, it is unlikely that our regression- and ROC-analyses were strongly biased by a relationship between gait speed and Get-up-and-go. On the other hand, since slight sampling errors can affect outcome parameters, it may be assumed that gait analysis at a higher sampling rate (>100 Hz) could improve the accuracy of step-time asymmetry and step/stride regularity calculations, and thus reduce the heterogeneity within YC, OC and EFR in our study.

We can conclude that for all participants together, the assessment of gait speed and regularity of steps and strides using 3D-accelerometry shows good to excellent reliability, especially when based on the average of two walks of 18 m. Several significant relationships with functional characteristics support the validity of these gait features for fall-risk estimation in elderly persons. However, only gait speed showed sufficient discriminative value for increased fall-risk in this study. More fundamental and prospective research aimed at identifying the underlying mechanisms of alterations in gait pattern and investigating the predictive value of 3D-acceleration derived gait features is necessary to clarify their clinical importance.

Acknowledgment

McRoberts (The Hague, The Netherlands) provided a 3D-accelerometer for the duration of the study.

Conflict of interest

All authors declare that they have no conflicts of interest.

Appendix A. Supplementary data


References


