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Reliability of gait variability assessment in older individuals during a six-minute walk test

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Abstract: Gait variability is an important indicator of gait performance. However, the reliability of the parameters used for its quantification, obtained from trunk linear accelerations, has still not been thoroughly investigated. The aim of this study is to assess the reliability of gait variability assessment in healthy older individuals based on lower trunk accelerations during a six-minute walk test and to examine the reliability of the data acquired in shorter periods. Twenty-nine subjects (84±5 years) performed the test while wearing one inertial sensor on the lower trunk. Gait variability parameters (standard deviation and coefficient of variation of the stride duration, and correlation coefficients of accelerations between neighbouring strides) were calculated from the accelerations over 35 rectilinear strides observed during six series of one-minute intervals extracted from the original signal. The reliability of these parameters was assessed using intraclass correlation coefficients (ICC). Results showed no significant changes across the six series for any of the parameters, with very high ICC values (0.93-0.95), indicating a strong reliability of the observed quantities. Therefore, gait variability analysis based on lower

trunk acceleration data is a reliable and informative quantity in gait performance assessment in older individuals, and one minute interval is sufficient to ensure reliable results.

1. Introduction

Gait in older population is characterised by progressive decrease in neuromotor control and balance disorders (Hausdorff et al., 2001; Helbostad et al., 2007). Assessment of gait patterns during normal overground walking is typically used for a better understanding of the postural control system and of its responses in the presence of aging effects (Morris et al., 2001; Tyson, 1999).

Among the parameters used to investigate older people walking, gait variability has recently gained popularity, being related to the underlying neural control of gait (Hausdorff, 2007). Its analysis allows the identification of changes in the postural control system due to aging, intervention or pathology, typically quantified through linear (standard deviation, SD, and coefficient of variation, CV) (Lord et al., 2011) or non-linear (Buzzi et al., 2003) descriptors of relevant variables.

The assessment of gait variability can be achieved using data measured with different methods, e.g. instrumented walkways (Brach et al., 2010; Paterson et al., 2009), or inertial measurement units (IMUs) (Annegarn et al., 2012; Riva et al., 2014). Using IMUs, it has been shown that increased interstride variability in the sagittal plane and decreased variability of trunk movements in the frontal plane, allow discriminating frailest older individuals (Moe-Nilssen and Helbostad, 2005). Moreover, significantly increased variability along the medio-lateral direction has been reported for patients with chronic obstructive pulmonary disease (Annegarn et al., 2012). Gait pattern characteristics, as observed at trunk level, can hence be expected to be clinically relevant.

Despite the widespread use of gait variability analysis, knowledge about its reliability is still limited. This, together with the lack of standardized testing protocols, limits variability analysis interpretation and understanding both for diagnostic and prognostic purposes in older population

(Lord et al., 2011). Reliable data can be obtained when investigating spatio-temporal parameters variability by means of an instrumented walkway if analysing at least 35 steps (Galna et al., 2013; Hollman et al., 2010). However, to the authors' knowledge, no specific indication is available for the reliability of other gait parameters, such as those obtained from acceleration signals, which allow to record the motion continuously over longer distances, thus potentially resulting in more reliable estimates of gait variability. The purpose of this study is to assess the reliability of gait variability parameters extracted from lower trunk acceleration signals during the six-minute walk test (6MWT) performed by healthy elderly adults.

2. Methods

2.1. Participants

Twenty-nine elderly subjects, able to independently walk 10 metres, without neurological disorders that could affect their performance and/or behaviour and with a Mini–mental state examination score (≥22/30) (Folstein et al., 1975) participated in the study (Table 1), conducted at three different retirement homes in Vienna. The chosen sample sized allowed to reach a moderate effect size (f=0.50) with power=0.95 (α=0.05) for a repeated measures ANOVA. Informed consent was obtained from all participants.

[TABLE1]

2.2. Experimental procedure

A 6MWT was used to investigate gait variability. This test evaluates an individual's functional capacity by measuring the distance a patient can walk in six minutes at their maximum speed. Participants were asked to perform the 6MWT wearing their regular shoes (Guyatt et al., 1985). They were asked to walk back and forth along a 30m straight pathway (turning 180° at each end of the pathway) and to cover the maximum possible distance (6 minutes walk distance, 6MWD) by walking as fast as they could. An IMU (FreeSense, Sensorize

s.r.l Rome; fs=200 Hz) was positioned over their lower lumbar spine using an elastic belt (Annegarn et al., 2012), which provided three linear acceleration and three angular velocity components. This data allowed to perform both gait parameters and upper body acceleration analyses.

2.3. Data analysis

Recorded signals were filtered with a 4thorder Butterworth filter (cut-off frequency of 20 Hz) (Mazzà et al., 2009). The IMU reference frame was rotated around the medio-lateral and antero-posterior axes, as measured while the subject was standing upright, to align the unit local axes with the three body anatomical axes (antero-posterior: AP, medio-lateral: ML, and vertical: V). No further correction was applied to the data.

The acquired signals were initially segmented into 6 one-minute windows. Within each window, the first rectilinear walking part was isolated using the gyroscope data measured around the vertical axis to discard the turning parts. In each of these rectilinear parts, the peaks of the antero-posterior accelerations (Zijlstra and Hof, 2003) were used to detect the beginning of a stride cycle and to calculate the stride duration (T). The first series of 35 strides was found for each of the 6 one-minute windows, and these six stride series were considered for further analysis (Galna et al., 2013; Hollman et al., 2010).

The mean stride duration (M_T) and the root mean square values of each acceleration component (RMS_V, RMS_{ML}, RMS_{AP}) were computed from the original signals and their variation across the six stride series was observed to monitor changes in the overall walking pattern that could be generated, for example, by fatigue.

The variability of the stride duration was calculated by combining interval information from all strides within each series, and was assessed with the standard deviation (SD_T) and coefficient of variation (CV_T). The mean values of the unbiased autocorrelation coefficients of the three acceleration components, calculated over any two neighbouring strides ($\overline{AC}_V$, $\overline{AC}_{ML}$, $\overline{AC}_{AP}$),

were then computed to quantify between-stride acceleration variability using the method proposed by (Moe-Nilssen and Helbostad, 2004). These coefficients were calculated from the IMU data as follows:

$$AC = \frac{1}{N-|m|}\sum_{i=1}^{N-|m|} x_i x_{i+m} \quad (1)$$

where: x_i are the samples of the acceleration signals (i=1,...*N*) and m is the varying time lag between the overlapped signal windows. The computation of the unbiased autocorrelation coefficients was solved using the "xcov" algorithm (Matlab, MathWorks, Natick, MA) (Moe-Nilssen and Helbostad, 2004). Perfect replication of the signals between neighbouring strides would return AC=1. Large variations between neighbouring strides would give coefficients close to 0.

2.4. Statistical analysis

Statistical analysis was implemented using SPSS software (version 20.0, SPSS Inc.). The normal distribution of the analysed parameters (M_T, RMS_V, RMS_{ML}, RMS_{AP}, SD_T, CV_T, AC_V, AC_{ML}, AC_{AP}) was checked using Shapiro-Wilk's test. Based on the normality test results, parametric or non-parametric analysis was performed on gait variability parameters (SD_T, CV_T, AC_V, AC_{ML}, AC_{AP}) using a repeated measures ANOVA or a Friedman Test, respectively, for each of the six stride series (within factor: 1st through 6th series, α=0.05). The same analysis was used for M_T, and RMS_V, RMS_{ML}, RMS_{AP} values to check for variations in the overall gait pattern (e.g. due to possible fatigue). Post-hoc t-test analysis with Bonferroni correction was used when significant differences were found. Intraclass correlation coefficients (ICC, two factor, mixed effects model) were used to assess within-session reliability for each gait variability parameter measured over all six stride series.

The correlation between gait variability measures and subjects' functional capacity was assessed with the Pearson's (R) correlation coefficient between the computed variability parameters and the 6MWD.

3. Results

All the subjects were able to complete the 6MWT, with an average 6MWD of 330±75 m, which is much lower value than that typical of healthy individuals (Du et al., 2009; Enright and Sherrill, 1998). No statistically significant differences between the six stride series were found for the gait variability parameters (SD_T, CV_T, AC_V, AC_{ML}, AC_{AP}). For the M_T, a significant difference was found among the six stride series ($F_{5,28}$=18.437, P<0.001). Post-hoc testing revealed that M_T increased by 5.5% between the 1st and the 6th series (t-test, p<0.001). A significant decrease was observed in RMS_V (x_{28}^5=31.327, P<0.001) and RMS_{AP} (x_{28}^5=13.847, P<0.05) during the 6MWT (Table 2).

[TABLE2]

Descriptive statistics of the temporal and trunk acceleration gait variability parameters is presented in Table 3 (mean and SD) and Figure 1 (median and quartiles of temporal parameters) for each of the six series of strides. No significant changes and strong reliability values were found during the 6MWT (ICC equal to 0.95 and 0.94 for SD_T and CV_T, respectively).

[TABLE3]

[FIGURE1]

Figure 2 shows the descriptive statistics of the parameters extracted from the trunk acceleration signals for the six stride series. No significant changes and a strong reliability was found for all the acceleration components, with ICCs values equal to 0.93, 0.95 and 0.93 for $\overline{AC}_V$, $\overline{AC}_{ML}$, and $\overline{AC}_{AP}$ respectively. Moreover, across all stride series $\overline{AC}_{AP}$ and $\overline{AC}_V$ were significantly higher than $\overline{AC}_{ML}$ (t-test, p<0.001).

[FIGURE2]

The 6MWD was found to present a significant negative correlation with SD_T (R=-0.57, p=0.001) and CV_T (R=-0.60, p=0.001) and a significant positive correlation with $\overline{AC}_V$ (R=0.57, p=0.001).

4. Discussion

The aim of this study was to assess the reliability of gait variability parameters as extracted from lower trunk acceleration signals in a group of healthy elderly subjects during a 6MWT. Reported results showed no significant changes during the six minutes for any of the investigated gait variability parameters, with reported ICC values indicating a strong reliability (Shrout and Fleiss, 1979) of all the observed quantities. The generalisation of these results to data obtained from sensors located on different parts of the body would require further investigations.

Reported variability values were similar to those previously reported for geriatric subjects (van Iersel et al., 2007) and remained reliable throughout the six minutes. This was true despite the fact that the 6MWT might have actually fatigued the subjects (Kervio et al., 2003), as suggested by the increase in the average stride duration observed in the last minute of the trial. Further study would be needed to investigate more thoroughly this assumption and prove the robustness of gait variability to fatigue.

Results obtained by calculating stride variability from 35 strides confirmed those obtained with an instrumented walkway (Galna et al., 2013), suggesting that highly reliable assessment of stride-to-stride fluctuations do not require prolonged acquisitions. The same study (Galna et al., 2013) suggested that two minutes are needed to reliably assess gait variability through spatio-temporal parameters. Our results indicate that, when variability analysis is based on lower trunk acceleration data, 35 strides performed in a shorter period, less than one minute in our case, are

sufficient to assess gait variability with the same reliability as the 6MWT. This is especially important for older persons as it implies that testing could be performed with less physical demand.

Trunk acceleration variability values were also in accordance with those previously reported for similar subjects during tests of shorter duration (Annegarn et al., 2012; Moe-Nilssen and Helbostad, 2005). In particular, it was confirmed that across all stride series $\overline{\mathrm{AC}}_{\mathrm{AP}}$ and $\overline{\mathrm{AC}}_{\mathrm{V}}$ were significantly higher than $\overline{\mathrm{AC}}_{\mathrm{ML}}$ (Helbostad et al., 2007), indicating that larger variations were found between neighbouring strides in the ML direction. It has been suggested (Annegarn et al., 2012; Mazzà et al., 2008; Moe-Nilssen and Helbostad, 2005) that variability in the ML direction may be related to different balance control mechanism than variability in the two other directions. Further studies are needed to elucidate whether this is solely the result of a lower signal-to-noise ratio associated with the acceleration signals in the ML components typically being the lowest in amplitude.

A limitation of this study is that, due to the limited number of collected consecutive strides, the assessment of variability was only based on linear techniques. Further studies, including the collection of longer stride series, would be required to include non-linear analysis tools. A further limitation might be that the subjects knew beforehand that the task duration was of six minutes and might have adjusted their walking strategy accordingly. Despite this hypothesis might be discarded according to indications available in the literature (Kosak and Smith, 2005), further studies might be needed to elucidate this aspect.

The reported results suggest that gait variability is a suitable assessment of elderly subjects' gait performance. Both temporal and trunk acceleration parameters, in fact, were correlated to the functional capacity of the subjects with the subjects who were able to walk further being those with smaller stride time variability and smaller vertical trunk acceleration variability. However, these correlations were only moderate and further studies on a larger sample are needed to draw stronger conclusions.

According to the reported results, it can be concluded that: a) gait variability, as measured both in terms of temporal and trunk acceleration parameters by an IMU located on the lower trunk, is a reliable and informative quantity in the assessment of gait performance in healthy elderly subjects; b) a shorter version of the 6MWT, reduced to one minute, allows to reliably assess gait variability, ensuring less physical demand on the elderly population.

Conflict of interest statement

The authors have no conflicts of interest to report.

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Ethical Approval: The present study was conducted in accordance to the Austrian laws (including doctors Act, CISA, Data Protection Act), the Declaration of Helsinki (as revised in Edinburgh 2000) and in analogous accordance with ICH-GCP Guidelines. Written informed consent was obtained from all participants. This study was approved by the ethics committee of the City of Vienna (EK-11-151-0811) and registered at ClinicalTrials.gov, NCT01775111.

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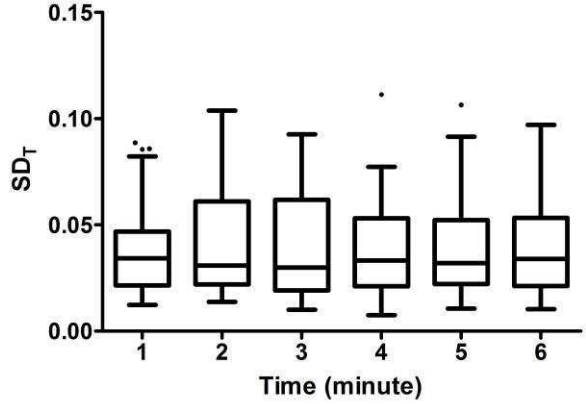
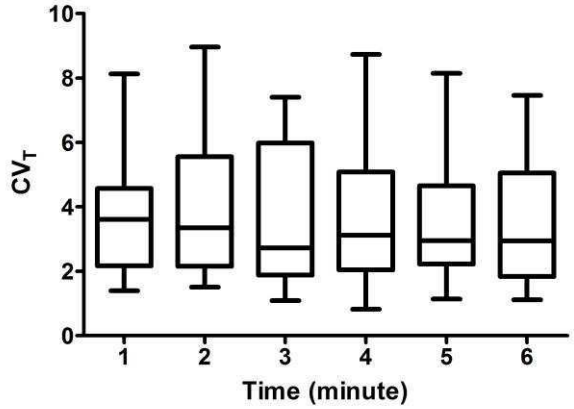
294

Figures

Fig. 1. Box-plots showing minimum, lower quartile, median, upper quartile, maximum, and outliers of: (a) standard deviation (SD_T), and (b) coefficient of variation (CV_T) of stride durations during the six stride series.

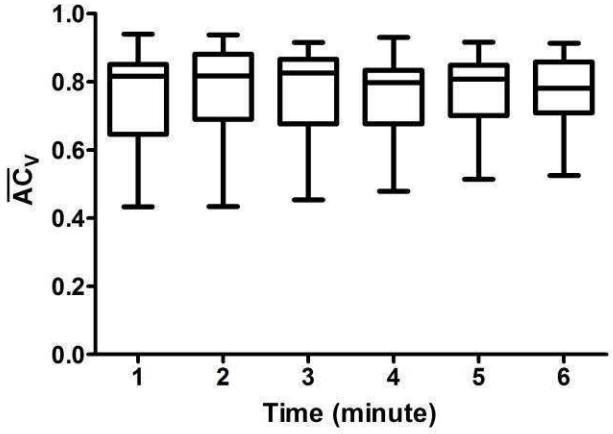


(a)

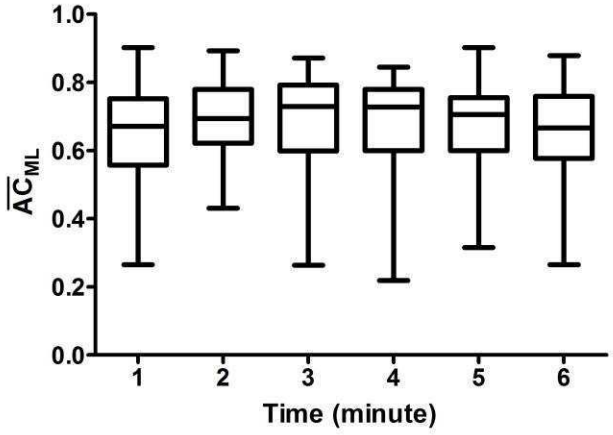


(b)

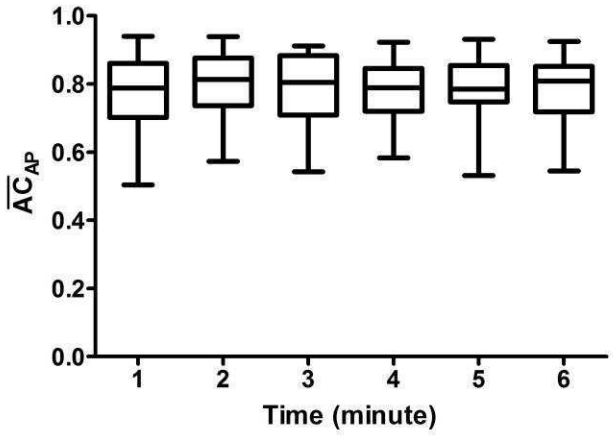
Fig. 2. Box-plots showing minimum, lower quartile, median, upper quartile, maximum, and outliers of interstride trunk variability AC along: (a) vertical: $\overline{\mathbf{AC}}_{\mathbf{V}}$, (b) medio-lateral: $\overline{\mathbf{AC}}_{\mathbf{ML}}$, and (c) antero-posterior: $\overline{\mathbf{AC}}_{\mathbf{AP}}$ anatomical body axes during the six stride series.



(a)



(b)



(c)

TABLE 1 Anthropometric characteristics of subjects. Value expressed as mean ± standard deviation

	N = 29
Women	24
Men	5
Age (years)	84±5
Mass (kg)	75±15
Height (m)	1.59±0.08
BMI (kg/m^2)	30±6

TABLE 2 Mean stride duration (M_T) and acceleration root mean square (RMS) of each axis (V: vertical, ML: medio-lateral, AP: antero-posterior) during the six-minute walk test (6MWT). Data are expressed as median ± IQR except for M_T reported as mean ± standard deviation (n = 29).

	1st series	2nd series	3rd series	4th series	5th series	6th series	P
M_T	1.03±0.12	1.06±0.11	1.07±0.11	1.08±0.12	1.09±0.12	1.09±0.13	<0.001
RMS_V	1.95±0.96	1.82±0.93	1.88±1.04	1.87±0.88	1.83±0.85	1.81±0.93	<0.001
RMS_{ML}	1.31±0.62	1.28±0.58	1.28±0.58	1.32±0.60	1.30±0.67	1.33±0.58	0.759
RMS_{AP}	1.23±0.49	1.19±0.44	1.18±0.42	1.17±0.41	1.15±0.42	1.16±0.37	0.017

TABLE 3 Standard deviation (SD_T) and coefficient of variation (CV_T) of the stride duration and mean values of interstride trunk variability ($\overline{\mathbf{AC}}$) along the three anatomical body axes, for each of the six series of strides (n = 29). Value expressed as mean ± standard deviation.

(s)	1st series	2nd series	3rd series	4th series	5th series	6th series
SD_T	0.04±0.02	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02	0.04±0.02
CV_T	3.85±2.19	4.18±3.02	3.83±2.20	3.59±1.95	3.61±1.98	3.48±1.78
$\overline{AC}_V$	0.74±0.15	0.78±0.12	0.77±0.12	0.76±0.11	0.78±0.11	0.77±0.10
$\overline{AC}_{ML}$	0.65±0.15	0.69±0.12	0.68±0.16	0.67±0.16	0.68±0.14	0.66±0.14
$\overline{AC}_{AP}$	0.77±0.10	0.79±0.09	0.78±0.10	0.78±0.10	0.78±0.10	0.78±0.10