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Toward ambulatory balance assessment: Estimating variability and stability from short bouts of gait



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ABSTRACT

Stride-to-stride variability and local dynamic stability of gait kinematics are promising measures to identify individuals at increased risk of falling. This study aimed to explore the feasibility of using these metrics in clinical practice and ambulatory assessment, where only a small number of consecutive strides are available. The concurrent validity and reliability were assessed compared to more continuous walking. Twenty young adults walked continuously for 500 m, as well as 36 bouts of 20 m while wearing an accelerometer (DynaPort MiniMod) on the trunk. Within-day reliability was high for stride time variability, mediolateral trunk variability and local dynamic stability, while between-day reliability was low for both variability estimates and moderate for local dynamic stability. Stride time variability and mediolateral trunk variability were increased when walking short bouts and did not correlate well with the longer walking trials. Local dynamic stability did correlate highly between the long and short bouts trials, and 15 bouts of eight strides appeared to be sufficient for valid estimation. These results imply task-specific differences and low reliability of variability estimates rendering them unsuitable for application to short bouts of gait, while local dynamic stability can be readily employed.

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1. Introduction

Falls are a major problem among patient and older populations [1,2]. For fall prevention interventions to be effective [3], individuals at risk need to be identified. Unfortunately, available fall risk prediction models [4,5] based on factors such as previous falls, low muscle strength, gait and balance impairments, and the use of certain medication, provide only fair to moderate predictive ability [5,6]. Therefore, additional measures are required to complement fall risk assessment, particularly those that can be easily measured clinically or during every-day ambulation.

A fall risk assessment needs to be able to quantify one's ability to deal with small perturbations that occur naturally during gait, for example, due to neuromuscular noise or irregularities in floor surfaces. Specifically, stride-to-stride variability of spatial and temporal parameters reflects the amount and magnitude of such experienced perturbations [7], while local dynamic stability quantifies the system's response to these perturbations in real

time [8]. Both variability and local dynamic stability are sensitive to aging and appear to be affected in fallers [7,9–15]. However, the relationship between these measures and fall risk has been established only under laboratory conditions, where continuous data series exceeding 200 strides are required for precise estimation [16,17]. For clinical use and ambulatory assessment, it is questionable whether it is feasible to collect datasets containing such large numbers of consecutive strides; hence their estimation based on short bouts of gait would be preferable.

A few studies have utilized short bouts of gait to estimate variability and local dynamic stability. These studies have shown that it is possible to detect balance impairments using this methodology, and suggested improved precision when averaging over an increasing number of bouts [18,19]. However, none of these studies investigated concurrent validity with reference values based on a long trial of at least 200 consecutive strides. In addition, the number of bouts required for their reliable estimation remains to be elucidated. Therefore, our primary aim was to investigate whether multiple short bouts of gait can be used for the valid and reliable assessment of variability and local dynamic stability, and how many bouts are required for their reliable estimation.

One important assumption when estimating variability and local dynamic stability is that data are stationary, meaning that

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statistical properties, such as the mean and variance of the analyzed signal, do not change over time. However during walking, mild non-stationarities can occur [8], which hamper the estimation of variability and local dynamic stability. This is particularly a problem for over-ground walking, where walking speed and foot placement are less constrained than during treadmill walking. A solution could be to employ a windowed approach, where the data series are cut into a number of short stationary bouts, and estimates are averaged over these multiple bouts. A secondary aim of this study was to investigate the stationarity of a long trial of over-ground walking and employ a windowed approach, when deemed necessary, to obtain reference values.

2. Method

2.1. Participants

Twenty healthy young adults participated after providing informed consent. Their mean age was 28.5 (± 3.3) years, height was 1.76 (± 0.10) m and weight was 66 (± 10) kg. The protocol was approved by the local ethical committee.

2.2. Experimental setup

The participants were fitted with an accelerometer (DynaPort MiniMod, McRoberts, Den Haag, the Netherlands) over the spine at the level of L5, attached to a neoprene belt around the pelvis. This accelerometer measured linear trunk accelerations in three directions (roughly corresponding to anteroposterior, mediolateral, and vertical) during all trials at a sample rate of 100 samples per second and in a range of ± 6 g.

The participants were asked to walk on a straight, tarmac outdoor footpath at their preferred walking speed. They completed two long trials of 500 m each and a trial consisting of 37 bouts of 20 m, all in the same session. The short bouts were achieved by walking between two traffic cones, which were placed on the first section of the 500 m path. The order of the trials was randomized, and participants were seated for a minimum of two minutes between the three trials. The short bouts trial was repeated on average 2.6 (± 0.5) months later to investigate test–retest reliability.

2.3. Analysis

Strides were defined as the time between each first and third peak in the vertical acceleration of the trunk accelerometer using MATLAB (version 7.12, The MathWorks BV, Natick, USA). For the long trial, the middle 200 strides were analyzed to attain adequate precision [16,17], and for the short bouts trial, the middle eight strides were analyzed to ensure steady state gait.

Stride time variability was estimated as the standard deviation of stride time. For mediolateral trunk variability, trunk accelerations in the mediolateral direction were first normalized to 99 samples per stride (average duration of a stride in this study). At each sample, the standard deviation over the different strides was calculated, and the average of these standard deviations was used as index of mediolateral trunk variability.

Short-term, finite-time local dynamic stability was estimated to assess local dynamic stability. The data series length was normalized to on average 99 samples per stride to eliminate the effect of varying data series length on the local dynamic stability estimates [16,20]. Subsequently, a state space was reconstructed using all three accelerations and their time-delayed copies [21,22]. The number of embedding dimensions was estimated from the long trials using the global false nearest neighbor routine [23], and a 9D state space was found to be appropriate. A fixed time delay of 1/4 of the average stride time was employed to avoid time-delay

dependent problems [24]. For each point in the state space the nearest neighbor was located and the Euclidian distance between these points was tracked over strides, resulting in multiple divergence curves [21]. The log of the mean divergence curve was taken, and the slope between 0 and 0.5 strides was calculated as the local dynamic stability estimate [8], expressing the average exponential rate of divergence after small perturbations of nearby orbits in state space. A positive estimate indicates that systems with small initial differences will behave differently in the future, hence the system is considered locally unstable [21].

2.4. Statistics

Stationarity of the long trial was investigated using Runs-tests on stride time, average acceleration per stride and variance per stride. Runs-test for randomness tests whether the distribution within a time-series is random or whether differences in series of estimates that are adjacent above or below the median value exist. When Runs-test indicated non-stationarity, variability and local dynamic stability were estimated using a sliding window of eight strides. These estimates were averaged over all windows and both long trials, to obtain a reference value for the long trial. The reference estimates were compared to those obtained with the original, non-windowed method using paired *t*-tests or related samples Wilcoxon signed rank test to detect differences between both methods, and Pearson correlation coefficients to investigate their consistency.

The first bout of the short bout trial was different from all other bouts and was therefore omitted from further analysis, leaving 36 bouts. To investigate whether short bouts of gait could be used to estimate variability and local dynamic stability in a valid manner, the estimates were averaged over all remaining bouts and subsequently compared to the reference values of the long trial. This was done by means of a paired samples *t*-tests or related samples Wilcoxon signed rank, and Pearson's correlation coefficients.

Within-day and between-day reliability were investigated using intra-class correlation coefficients (ICC: 2.1) absolute agreement [25] between the first half and second half of the short bouts trial, and between the short bouts trial and the repeated session. In addition, the smallest individual change that can be determined with 95% confidences, i.e. the smallest detectable difference (SDD), was estimated. These smallest detectable differences were expressed in percentages of the mean to maintain comparability with other studies since methodological choices such as state space reconstruction or data series length have a large influence on mean values of local dynamic stability [20,21,24].

To determine the number of short bouts required for estimation of variability and local dynamic stability, estimates were averaged over an increasing number of bouts. One to thirty-six bouts were randomly extracted without replacement and their variability and local dynamic stability estimates were averaged. The averaged estimates were correlated to the reference values obtained from the long trial, and the explained variance (r^2) was calculated. This procedure was repeated 1000 times to increase precision, and results were averaged over an increasing number of bouts. The improvement in r^2 was evaluated to assess the number of short bouts required. A *p*-value < 0.05 was considered statistically significant.

3. Results

Runs-test indicated non-stationarities in 16 out of the 20 participants, mainly in average acceleration per stride in the anteroposterior and vertical direction and stride time. Variability

was slightly lower, i.e. 0.003 sec for stride time variability ($p < 0.001$) and 0.006 g for mediolateral trunk variability ($p < 0.001$), using the windowed analysis when compared to the original, non-windowed method (Fig. 1). No mean testing was performed for local dynamic stability as data series length differed between both methods and this influences the mean of the estimate [21]. The correlation between the windowed method and the original method was very strong for both variability estimates ($r = 0.96$ and 0.91 , both $p < 0.001$) and strong for local dynamic stability ($r = 0.84$, $p < 0.001$). Therefore, the variability and local dynamic stability estimates based on the windowed analysis were used as reference values for the long trial in further comparisons.

Stride time, stride time variability and mediolateral trunk variability, were all significantly higher in the short bouts trial than in the long trial (all $p \leq 0.002$). There was no significant difference between both trials for local dynamic stability ($p = 0.41$) (Table 1 and Fig. 2). The correlations between both trials were low for stride time variability and mediolateral trunk variability ($r = 0.27$ and 0.42 , both $p \geq 0.06$), and strong to very strong for stride time and local dynamic stability ($r = 0.94$ and 0.89 , $p < 0.001$).

Within-day reliability was high for all measures; ICC was 0.90 for stride time variability, 0.92 for mediolateral trunk variability and 0.82 for local dynamic stability (all $p < 0.001$). Between-day reliability was lower, i.e. ICC 0.42 ($p = 0.03$) for stride time variability, 0.53 ($p = 0.008$) for mediolateral trunk variability and 0.67 ($p < 0.001$) for local dynamic stability. The smallest detectable differences using these measures were, respectively, 120%, 63%, and 21% of the mean.

Since the test–retest reliability of both variability measures was low, only the local dynamic stability was used to investigate the number of short bouts required for valid estimation. With 15 included bouts, the explained variance (r^2) was 72% and the improvement when including more bouts was less than 1% (Fig. 3). The resulting correlation between these 15 short bouts and the long trial was 0.85. When including only 15 bouts, the between-days ICC was 0.60 ($p = 0.006$) with a SDD of 25%.

4. Discussion

Variability and stability measures, quantifying the ability to deal with small perturbations that occur naturally during gait, appear to be related to fall risk and could be helpful in the identification of fall-prone individuals. To explore the feasibility of these measures for clinical practice and ambulatory assessment, we investigated whether multiple short bouts of gait could be used

for valid and reliable estimation, and how many bouts were minimally required.

Stride time, stride time variability and mediolateral trunk variability were higher during the short bouts than when walking a long distance, while local dynamic stability was comparable. An increase in stride time when walking a short distance was also observed by Najafi et al. [26], who suggested that the selection of a walking strategy is task dependent. There was a difference in task between the different trials in our study, i.e. participants walked short distances and were instructed to walk for a fixed period of time during the short bouts trial, whereas they walked a lengthy fixed distance during the long trials. Nevertheless, the low correlation between trials for both variability measures, despite their high within-trial reliability, indicates that for these measures a difference in task does not only lead to an offset but also to random variation. As variability measures estimated from long trials under standardized conditions have been linked to falls [9,10,15], it is doubtful whether variability measures in their current form can be used to obtain comparable information from short bouts of gait. For local dynamic stability, results were more promising as these estimates based on short bouts of gait did not differ from those obtained from the long reference trial. Moreover, the correlation between both trials was high, indicating that estimates could be interchanged.

Reliability of estimates based on short bouts of gait was high within-days, while for stride time variability and mediolateral trunk variability between-day reliability was low and corresponding SSDs were high. For local dynamic stability between-day reliability was moderate and comparable to those obtained for the long trials [24]. The between-day reliability of both variability measures in this study was comparable or slightly lower than has been reported for older adults [19,27,28]. A possible explanation might be that older adults are probably more heterogeneous due to co-morbidities than the participants in this study, and such an increased between-subject variation with a maintained within-subject variation can result in higher ICCs. The low between-day reliability and high smallest detectable differences of mediolateral trunk variability could be caused by a difference in attachment of the accelerometer between days. However, the difference in reliability of the orientation-invariant stride time variability and local dynamic stability suggests that these variations are more likely caused by other sources, such as time of the day or even mood. To verify this, we realigned the accelerometers in an additional analysis, based on their orientation with respect to gravity to identify the vertical and optimized the harmonic ratios to identify the mediolateral and anteriorposterior direction and

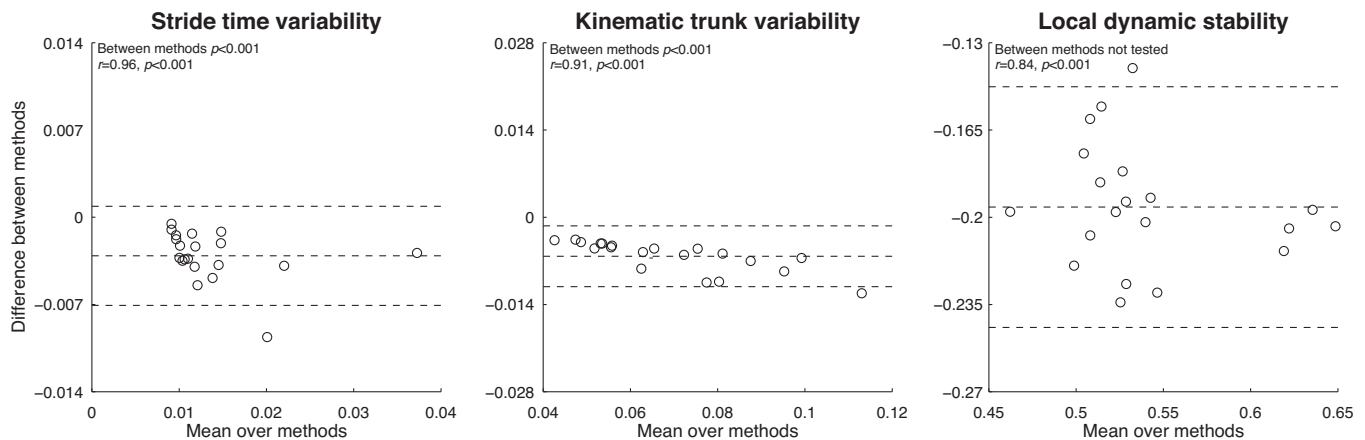


Fig. 1. Bland–Altman plot of the original, non-windowed method and windowed analysis of the long trial. Each circle is an individual subject and the dashed lines are the mean and the 95% limits of agreement. Stride time variability is expressed in seconds, mediolateral trunk variability in g and local dynamic stability per stride. Scaling of the x-axis and y-axis is equal within this figure, allowing for easy comparison over measures.

Table 1

Comparison of the long and short bout trial, means with standard deviations between brackets.

	Stride time in seconds	Stride time variability in seconds	Mediolateral trunk variability in g	Local dynamic stability expressed per stride
Long trial windowed analysis	0.99 (0.05)	0.012 (0.006)	0.07 (0.02)	0.44 (0.05)
Short bout trial	1.01 (0.05)	0.026 (0.015)	0.09 (0.03)	0.44 (0.05)
Correlation between trials	$p = 0.001^*$ $r = 0.94$ $p < 0.001$	$p < 0.001^*$ $r = 0.27$ $p = 0.25$	$p = 0.002^*$ $r = 0.42$ $p = 0.06$	$p = 0.41^*$ $r = 0.89$ $p < 0.001$

* Asterisked p -values denote paired samples t -tests or related samples Wilcoxon signed rank tests results between the long and short episodes trials.

examined the between-day reliability again. We also tested the between-day reliability of the Euclidean norm of the 3D accelerations, which are orientation-invariant. Neither analysis yielded improved reliability. Our findings could have implications for other research, as variability seems to be task-dependent and sensitive to the moment of measurement. For local dynamic stability, smallest detectable differences were 21%. To put this in perspective, the difference in local dynamic stability between fallers and non-fallers has been reported to be between 6 and 20% [10,12]. Nevertheless, as we measured typically quite stable subjects, the smallest detectable difference expressed in percentages of this mean could be overestimated. We therefore expect that in older adults smaller differences might be detected.

A minimum of 15 short bouts was necessary to obtain comparable estimates for local dynamic stability compared to the long reference trial. The decision on the number of bouts required relies on the size of the expected effect and whether differences on a group or individual level will be evaluated. When analyzing only 15 bouts, between-day reliability was still moderate, but smallest detectable differences were slightly larger than when including all 36 bouts. Given these results, clinical application appears limited as measuring 15 bouts of eight strides would be demanding for the patient and is time consuming. However, assessment of local dynamic stability based on short bouts of gait seems possible.

In some of the long trials, non-stationarities were observed; hence a windowed analysis was employed to obtain reference values. Variability estimates obtained using this windowed analysis were highly correlated with, and significantly lower than estimates based on the whole trials. This offset could be caused by an underestimation of the standard deviation given the low number of included samples [29] or by the elimination of variation at longer time scales than eight strides, which could be due to the

non-stationarity. Since the correlation between both methods was high, the windowed analysis was deemed suitable to serve as reference values for the validation of the short bouts.

Our study provides valuable information regarding the use of short bouts of gait for the assessment of variability and local dynamic stability, yet there are some limitations. The subjects walked on even flooring and only straight walking was analyzed, while during ambulatory measurements flooring will differ and only a small portion of daily-life walking occurs in a straight line. Furthermore, comparable to daily-life, walking speed was uncontrolled but we expect variations in walking speed to be larger in daily-life where obstacles and turns occur. Future studies should investigate whether data obtained from daily-life gait, where these variations do occur, can be used to reliably assess the risk of falling. Moreover, we observed a difference in stride time between the long trial and short bouts trial. This difference was small and diminished by the time-normalization employed before calculation of mediolateral trunk variability and local dynamic stability but strengthens the notion that task dependent differences occur between walking short bouts and long distances. In addition, the number of embedding dimensions used in this study, i.e. nine, was higher than in many other studies [8,12,16,20] but is still within the range of five to twelve used in the literature [8,10,12–14,16,18,20,24,30]. This broad range of embedding dimensions might be due to the use of different types of data, such as electromyography, joint angles, angular velocity or linear accelerations, and the embedding of one single signal or more; and might call for standardization of state space reconstruction in gait research. In the current study, the global false nearest neighbor routine was used to determine the appropriate number of embedding dimensions and 9D was deemed suited. As local dynamic stability estimates based on a 6D and 12D state space correlated highly with those of the employed 9D state space

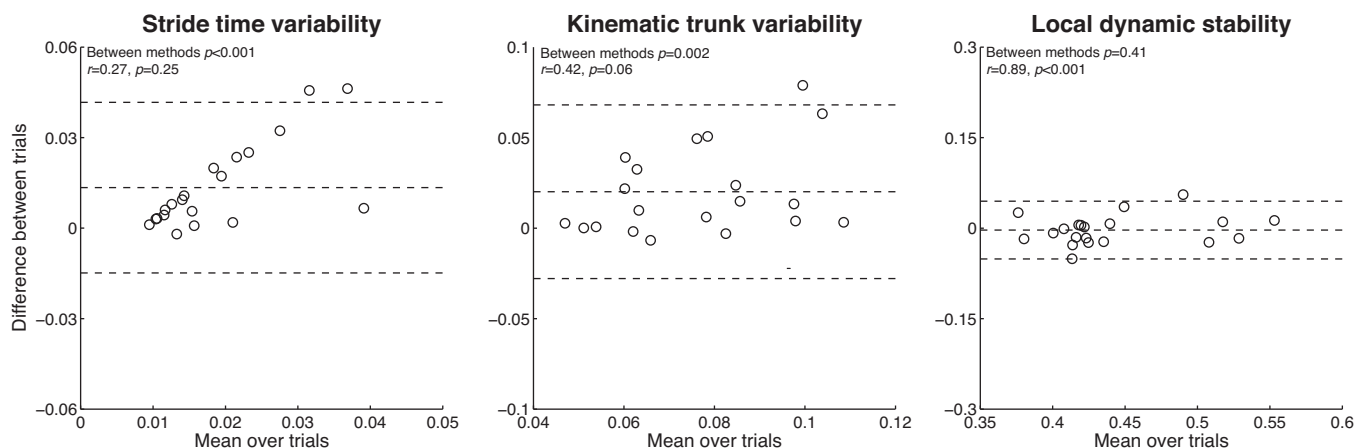


Fig. 2. Bland–Altman plot of the long and short bouts trial. Each circle is an individual subject and the dashed lines are the mean and the 95% limits of agreement. Stride time variability is expressed in seconds, mediolateral trunk variability in g and local dynamic stability per stride. Scaling of the x-axis and y-axis is equal within this figure, allowing for easy comparison over measures.

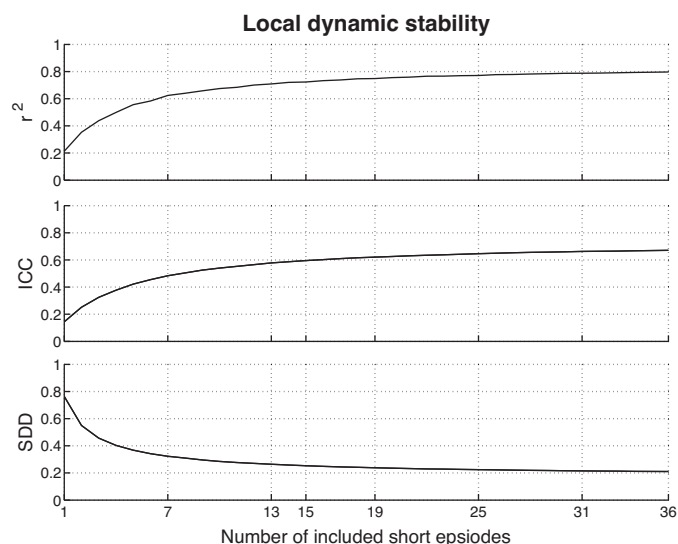


Fig. 3. Estimation of the number of required short bouts. Lines indicate the portion of variance (r^2) of local dynamic stability from the long trial that is explained by local dynamic stability from the short bouts trial, and the corresponding between-day intraclass reliability coefficient (ICC) and smallest detectable difference (SDD), all dependent on number of episodes averaged.

(respectively, $r \geq 0.94$ and $r \geq 0.81$), the number of embedding dimensions had minor effects. Finally, participants were healthy young adults, while the eventual application of these measures will be to the more fragile, older population. Future studies should investigate the usability of local dynamic stability based on ambulatory measurements in older adults and its predictive value for prospective falls.

Overall, our results indicate that despite encouraging results in laboratory studies, variability measures in their current form do not appear to be useful on short bouts of gait. In contrast, local dynamic stability can be reliably assessed from short bouts of gait. The number of required bouts of strides for valid estimation of local dynamic stability possibly limits its use in clinical assessment, highlighting the importance of estimation based on daily-life ambulation, where multiple bouts can be recorded over a longer period.

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Conflict of interest statement

None of the authors of this paper had any conflict of interest that could inappropriately influence (i.e., bias) the presented work.

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