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Two-year changes in gait variability in community-living older adults

Bård Bogen[a,*], Mona Kristin Aaslund[a], Anette Hylen Ranhoff[b], Rolf Moe-Nilssen[a]

[a] Department of Global Public Health and Primary Care, University of Bergen, Kalfarveien 31, 5018 Bergen, Norway
[b] Department of Clinical Science, University of Bergen, Postbox 7804, 5020 Bergen, Norway

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ABSTRACT

Background: Increases in stride-to-stride fluctuations (gait variability) are common among older adults, but little is known about the natural progression of gait variability with increasing age.
Research question: Does gait variability change with increasing age in a group of community-living older adults?
Methods: The participants were community-living volunteers between 70–81 years, who were tested with a two-year interval between tests. They walked 6.5 m under four different conditions: At preferred speed, at fast speed, during a dual task condition and on an uneven surface. Trunk accelerations in the anteroposterior (AP), mediolateral (ML) and vertical (V) direction were captured using a body-worn sensor worn at the lower back. Gait variability was estimated using an autocorrelation procedure, where coefficients tending towards 1.0 indicated low variability and 0.0 as high variability. To estimate change, we used an ANOVA-procedure with baseline gait speed as a covariate.
Results: At baseline, 85 older adults were tested, and data for 56 of these were available for analysis over a two-year period of time. The average age at inclusion was 75.8 years (SD 3.43) and 60% were women. During preferred speed walking, variability increased in the AP direction (mean difference 0.05, $p = .038$), during fast speed walking it increased in the V direction (mean difference 0.04, $p = .037$) and during dual task-walking, it increased in the ML and V directions (mean differences 0.03, $p = .032$ and 0.09, $p = .020$ respectively).
Significance: The findings from this study could be helpful for discriminating between normal and pathological progression of gait variability in older adults.

1. Background

One of the most prominent features of typical aging is the loss of mobility: Older adults walk outside less, they walk shorter distances and they walk more slowly [1]. Mobility limitations can be seen as the gap between environmental affordances and individual capabilities [2]. Impaired capabilities could be caused by disease and injury, as well as by gradual decline of organ systems, such as reduced muscle strength [3] and cognition [4]. Mobility limitations may be prevented or reversed [5], but for early identification of individuals at risk, assessment methods that are sensitive to subclinical gait deficiencies are needed. Walking speed is easily measured, and is in widespread clinical use. Further, preferred walking speed has been called “the sixth vital sign” due to its ability to categorize older people in terms of health and function, and in predicting adverse events [6]. However, walking speed is an unspecific measure, and characteristics of the gait cycles have been found to be more informative about gait-related attributes such as fall risk [7,8]. Such gait characteristics should therefore be investigated.

Fluctuations between gait cycles, also called gait variability, are normal in both young and old adults: One stride may resemble the next or the previous, but they are practically never identical. This variability allows for flexibility and adaptability under continually changing circumstances. However, too much variability between strides is unproductive, as the energetic cost of walking becomes higher [9], and balance becomes poorer [10]. It has been suggested that variability that is helpful in achieving a goal is “good” and that variability that hinders it is “bad” [11], and cut-offs for distinguishing between normal and pathological variability in gait have been suggested [12]. Gait variability may be measured using different methods, such as 3D-motion capture and electronic gait mats. Recent years have seen increased use of body-worn inertial sensors, that are relatively inexpensive and easy to use, both in lab- and other settings. Compared to gait mats that only register gait when the foot is in contact with the mat, sensors capture a continuous acceleration signal throughout the gait cycle, suggesting that this method may be preferable [13].

Sensor-derived gait variability is descriptive of gait patterns, which is not measured with gait speed. Measurements of gait variability can

* Corresponding author.
E-mail addresses: beb@hvl.no (B. Bogen), mona.aaslund@uib.no (M.K. Aaslund), ahranhoff@yahoo.no (A.H. Ranhoff), rolf.moe-nilssen@uib.no (R. Moe-Nilssen).

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be done easily in clinical settings, and may prove to be valuable tools for identifying early, subclinical gait pathology. However, to do so, it is important to establish what we would expect to see among older adults from a non-clinical population. Further, it is important to study if and how gait changes with normal aging, to be able to discern pathological from non-pathological changes. Finally, as unconstrained walking may not be challenging enough, gait should be studied under different conditions that may emphasize any walking difficulties [14].

Therefore, the aim of this study is to investigate how gait patterns, operationalized here as accelerometer-derived gait variability, changed over two years in a group of community-dwelling older adults, selected randomly from the electoral roll. As gait variability is associated with negative outcomes such as fall risk [7] and cognitive impairment [15], and as both falls and cognitive impairment are more prevalent with increasing age, we hypothesized that gait variability would increase over a period of two years.

2. Methods

2.1. Design

This was a study with a prospective observational design in a movement laboratory setting, where participants were tested on two occasions, with a two-year interval. A two-year follow-up period was chosen, as longer follow-up periods could have affected the retention rate, and shorter follow-up periods could have been too short for changes to occur.

2.2. Participants

Names and addresses of 400 men and women were selected randomly from the electoral roll. They were then contacted by letter and telephone, and invited to attend testing at a university movement lab. To be included, participants had to live in their own homes, be able to walk 10 m without walking aids, and be able to give informed consent. The aim of the study was to investigate gait changes in typically aging which is characterized by heterogeneity. To capture this, no exclusion criteria applied. The study protocol was approved by the regional ethics committee.

2.3. Procedures

The participants walked a distance of 10.5 m, where the middle 6.5 m were captured. Capturing started and stopped automatically with passing of photoelectric cells. Gait characteristics were registered using a body worn inertial sensor with a triaxial accelerometer (MTx, Xsens Technologies B.V., Enschede), fixed to the lower back with an elastic belt. The sensor sampled at 128 Hz after lowpass filtering at 55 Hz to avoid aliasing. Data was transmitted by Bluetooth to a laptop and then processed with in-house software. Waveform gait variability was estimated by using an unbiased autocorrelation procedure, where the acceleration time series from accelerations in three directions (anteroposteriorly; AP, mediolaterally; ML and vertically; V) were compared to a replicated time series which was time-lagged equal to one stride [16]. Hence a value tending towards zero would mean very high variability, while a value tending towards one would mean very little variability (please note that this wording is in contrast to previous reports using the same method, where the term ‘regularity’ has been used. Previously, ‘regularity’ was deemed most appropriate because of the nature of the metric (autocorrelation), where increases (towards 1.0) meant *less* stride-to-stride fluctuation, whereas an increase in variability would mean *more* stride-to-stride fluctuation. Due to widespread use in the research literature, we chose to use the term ‘variability’ in this paper, but emphasize here that lower autocorrelation means more stride-to-stride fluctuation). The method of autocorrelation for estimation of stride-to-stride fluctuations has been shown to be reliable and valid for older adults [17]. The method has been used in several studies of older populations with different clinical characteristics [18–21].

Basic spatiotemporal gait parameters were registered for background information. Cadence was estimated as 60*frequency (Hz)/ samples per step. Similarly, average step length (cm) was calculated as walking speed (cm/s)*samples per step/frequency (Hz). Further, the Walk ratio was calculated as step length/cadence. In healthy persons, the Walk ratio has been found to be invariant of speed, and is expected to be around 0.55–0.60 during unconstrained walking and at most speeds [22].

For a detailed report on the estimation of gait cycle parameters used in this study, see Moe-Nilssen and Helbostad [16].

The participants walked under four different conditions:

i) At their preferred speed across an even surface (“walk as you normally would”).
ii) At fast speed across an even surface (“walk as fast as you can without running or losing balance”).
iii) At preferred speed across an even surface while counting backwards from 50 with intervals of three.
iv) At preferred speed across a rubber mat with unevenly spaced convex circular bulges, covered by another mat (the participants were made aware that the underneath mat was irregular).

The participants walked back and forth for each condition, and the average of both walks was used for analysis.

2.4. Analysis

Data was analysed using IBM SPSS 17.0. Data are presented as means and standard deviations. Change over time was analysed using repeated measures ANOVA, with analysis of gait parameters under each condition analysed separately as dependent variables, and time entered as two levels: Baseline and two-year follow-up, as independent variables. We expected gait speed to be associated with variability [23], and therefore we did an analysis of bivariate correlation between speed and variability (Pearson’s r), and found significant correlation. Therefore, baseline speed values of each gait variable was entered as a covariate in the analyses [24]. Changes in cadence, average step length and the Walk ratio were analysed with speed during the respective conditions as a covariate. Eta partial squares were estimated for effect size.

3. Results

Names and addresses from 400 older adults between 70–81 years of age were provided, of these 85 were reached and agreed to participate. All participants who agreed to participate fulfilled the inclusion criteria of living in their own homes and being able to walk 10 m without walking aids. Age and gender was not significantly different between the 85 who participated and the 315 who did not participate. Of the participants from baseline, 58 returned for the two-year follow-up; however, data from two participants could not be used due to technical error (see Fig. 1). Participants who did not attend the two-year follow-up were not significantly different from those who attended with regards to age (did not attend: 75.0 (SD 3.1) vs did attend: 75.8 (SD 3.4), $p = .259$) or preferred gait speed (did not attend: 1.10 (SD 0.22) vs did attend: 1.15 (SD 0.21), $p = .297$).

The average age of the participants was 75.8 (SD 3.43) and 60% were women. On average, they used 2.11 medications regularly (medications for hypertension ($n = 22$) and hyperlipidaemia ($n = 13$) were the most common) and had 1.58 chronic diseases (cardiovascular disease ($n = 23$) and lower limb osteoarthritis ($n = 11$) were the most common). When asked about pain, nine participants reported that their worst pain was in their lower extremities, and the average numeric rating of pain in the lower extremities from 0 to 10 was 3.25.

Basic gait parameters (speed, cadence, average step length and Walk

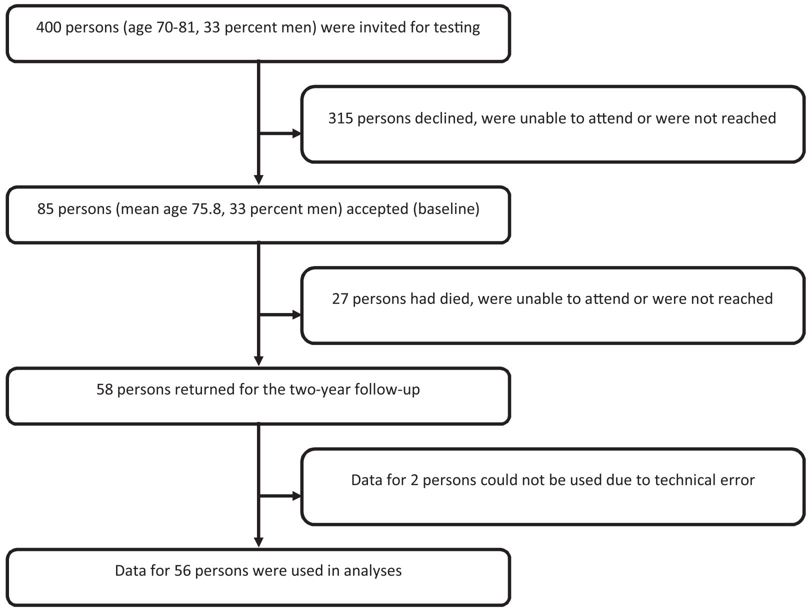

Fig. 1. Flow chart with overview of the study participants.

Table 1
Changes in basic gait variables (speed, cadence, average step length and walk ratio) over two years, under four different walking conditions[a].

		0 year mean	2 year mean	P-value	Effect size[b]
Preferred speed	Speed (m/s)	1.14 (0.21)	1.13 (0.22)	0.382	.014
	Cadence (steps/min)	108.01 (9.69)	109.25 (16.10)	0.552	.007
	Average step length (m)	0.63 (0.84)	0.62 (0.10)	0.441	.011
	alk ratio (m/step/min)	0.59 (0.07)	0.58 (0.11)	0.594	.005
Fast speed	Speed (m/s)	1.44 (0.25)	1.40 (0.26)	**0.021***	.096
	Cadence (steps/min)	122.32 (9.94)	121.74 (11.87)	0.644	.004
	Average step length (m)	0.70 (0.10)	0.69 (0.09)	0.208	.030
	Walk ratio (m/step/min)	0.58 (0.08)	0.57 (0.09)	0.617	.005
Dual task	Speed (m/s)	0.88 (0.28)	0.81 (0.27)	0.084	.061
	Cadence (steps/min)	89.49 (20.14)	86.71 (22.90)	0.344	.019
	Average step length (m)	0.58 (0.09)	0.56 (0.12)	0.175	.039
	Walk ratio (m/step/min)	0.68 (0.19)	0.68 (0.20)	0.968	.000
Uneven surface	Speed (m/s)	1.01 (0.27)	0.95 (0.23)	**0.024***	.090
	Cadence (steps/min)	101.62 (13.02)	101.83 (25.23)	0.952	.000
	Average step length (m)	0.59 (0.10)	0.57 (0.11)	**0.024***	.093
	Walk ratio (m/step/min)	0.58 (0.09)	0.57 (0.12)	0.553	.007

*$p \le 0.05$.
[a]Repeated measures ANOVA; walking speed analysed without covariates, cadence, step length and Walk ratio analysed with walking speed as covariate.
[b]Effect sizes calculated as partial eta squared.

ratio) changed little during the follow-up, except for decreases in fast walking speed, uneven surface walking speed and uneven surface step length (see Table 1).

In a bivariate analysis of correlation, there was a positive and linear correlation between gait variability and speed under all conditions. The correlations were strongest in the V direction (see Table 2). Further analyses of two-year change were therefore performed with baseline speed as a covariate.

AP variability increased significantly over two years for the preferred speed condition (mean difference 0.05, p = 0.034), ML variability increased significantly during the dual task-condition (mean difference 0.03, p = 0.032), while V variability increased significantly during the fast walking condition (mean difference 0.04, p = 0.037) and the dual task-walking condition (mean difference 0.09, p = 0.020). Variability did not change in any of the directions during uneven surface walking (see Table 3).

4. Discussion

The aim of this study was to investigate whether gait characteristics, operationalized as gait variability and spatiotemporal gait parameters, changed over a follow-up period of two years in a group of community-living older adults. To our knowledge, longitudinal assessment of sensor-measured waveform gait variability has not been done before. We hypothesized that variability would increase with increasing age, and our hypothesis was to some extent confirmed.

Although aging is a highly heterogeneous process, motor skills tend to deteriorate with increasing age. In previous cross-sectional studies, gait variability has been found to increase with age [25]. The biological origin of gait variability is complex, and associations have been found with sensorimotor factors, such as reaction time and proprioception [26]. Further, research points to changes in brain areas associated with sensory integration and lower limb coordination [27], and stride time-variability has been found to be associated with cognitive decline [28]. While our study provides no new information about the underlying causes of gait variability, the information about the natural progression

Table 2
Bivariate correlations between gait variability and gait speed under four different walking conditions[a].

		Preferred gait speed	Fast gait speed	Dual task gait speed	Uneven surface gait speed
Pref. speed	AP stride reg.	0.342**			
	ML stride reg.	0.400**			
	V stride reg.	0.644**			
Fast speed	AP stride reg.		0.368**		
	ML stride reg.		0.375**		
	V stride reg.		0.564**		
Dual task	AP stride reg.			0.708**	
	ML stride reg.			0.641**	
	V stride reg.			0.891**	
Uneven surface	AP stride reg.				.603**
	ML stride reg.				.727**
	V stride reg.				.785**

[a]Pearson's product moment correlation coefficient.
**$p \le 0.01$.

of gait variability with increasing age is relatively novel. Our findings suggest that even within a two-year window, gait performance tended to deteriorate in our sample of community-living older adults, which may be an indication of diminishing physiological functioning. Further, it may indicate that our participants were in a phase of accelerated mobility decline, which epidemiological data suggests starts around the sixth decade [1].

There was some increase in gait variability over two years; however, effect sizes are small and it is unclear to which degree these changes are meaningful or important. Brach and co-authors have made suggestions about meaningful change with regards to gait variability from footfall analysis [29]. For example, change of SD 0.014 s in stance time variability would correspond to a moderate effect size (Cohen's d). However, as the variability metrics from footfall analysis (standard deviations or coefficients of variance) are different from the variability metric in this study, extrapolating to our results can be challenging. One of the main reasons for using instrumented or digital movement analysis is the sensitivity to small movements that may be difficult to register visually. This begs the question about whether small movement disturbances that really are insignificant are registered. However, given the inherent instability of gait, with a top-heavy structure moving over a continually changing base of support, even small gait disturbances may have an impact. Maki, for example, found that a stride length variability of only 0.017 m (standard deviation) was associated with a doubled risk of falls [8]. Hence, the relatively small changes in gait variability in our sample may have had a noticeable impact on the participants, but the findings should be compared to an external criterion for more precise knowledge about the magnitude of the impact. It can also not be ruled out that a greater number of strides would give a more consistent performance, and longer walking distances could possibly have emphasized gait changes even more.

Gait speed is easily measured without specialized equipment and has been identified as a strong indicator of health status and as a predictor of adverse events in older adults [6]. At preferred and dual task-speeds, there were no significant changes in gait speed, while there were in variability in the AP direction (during preferred speed), and in the ML and V directions (during dual task). This could suggest that while gait speed was relatively well preserved, gait quality deteriorated. Gait speed can possibly be seen as a gross motor function that is responsive to relatively large changes in health status and bodily resources, while measurement of gait variability is sensitive to more subtle changes in consistency of coordination patterns. In another study, gait speed has been found to be controlled by different functional brain networks than gait variability [30], which at least in part could explain differences in how gait speed and variability develop over time. In our view, our findings emphasize the potential utility of sensor-based gait analysis, particularly for older persons with subclinical presentations of decline in health and function.

There was little change in spatiotemporal gait parameters during the follow-up period, which could suggest that the basic rhythm of gait was preserved, despite the subtle stride-to-stride variations that were apparent in the analyses of variability. In other studies, spatiotemporal variables have been studied, which allows for comparison. In a population-based study, Hollman and co-authors have found cadences of 102–106 steps/min for men and 113–114 steps/min for women in the same age groups as our study. Similarly, they found step lengths of

Table 3
Changes in gait variability (autocorrelation coefficient) under four different walking conditions over two years[a].

		0 year mean (SD)	2 year mean (SD)	ANOVA, with baseline speed as covariate (p-value)	Effect size[b]
Preferred speed	AP var. (autocorr.)	0.8 (0.10)	0.75 (0.15)	**.038***	.077
	ML var. (autocorr.)	0.58 (0.14)	0.56 (0.16)	.348	.016
	V var. (autocorr.)	0.79 (0.13)	0.74 (0.18)	.691	.003
Fast speed	AP var. (autocorr.)	0.79 (0.13)	0.75 (0.13)	.112	.048
	ML var. (autocorr.)	0.62 (0.15)	0.61 (0.17)	.243	.026
	V var. (autocorr.)	0.83 (0.13)	0.79 (0.18)	**.037***	.081
Dual task	AP var. (autocorr.)	0.69 (0.18)	0.63 (0.20)	.073	.067
	ML var. (autocorr.)	0.44 (0.18)	0.41 (0.19)	**.032***	.094
	V var. (autocorr.)	0.6 (0.24)	0.51 (0.27)	**.020***	.110
Uneven surface	AP var. (autocorr.)	0.74 (0.14)	0.68 (0.17)	.379	.015
	ML var. (autocorr.)	0.47 (0.17)	0.43 (0.19)	.074	.059
	V var. (autocorr.)	0.67 (0.18)	0.6 (0.22)	.166	.036

*$p \le 0.05$.
[a]General linear model with baseline speed values as covariates.
[b]Effect size calculated as partial eta squares.

69–68 cm for men and 61–59 for women [31]. These findings are relatively comparable to the results in the present study (Table 1). Lee et al. found that cadences dropped with 1–2 steps per minute and step lengths with approximately 3 cm per step during dual task walking [32]. The drop in step length is comparable to our study, but the drop in cadence is greater, possibly because the participants walked with lower cadence during single task, and also because the additional task was a manual task and not a cognitive task. We argue that well-known gait parameters do not differ greatly between our study and other studies, which could suggest that the variability measurements are applicable to other populations.

As suggested in the introduction, variability is not inherently “bad” or “good”. Too little variability could be sign of a lack of flexibility and adaptability, while too much variability could be seen as neuromuscular “noise” and low balance control during walking [12,33]. There may therefore be an optimal window of variability that is neither too great or too small. In one study, both too much and too little step width variability was found to be associated with a fall history [34], and in another study, frail older adults walked with lower ML variability than fit older adults [19]. In the latter study, the authors suggest that the frail participants may have walked with a strategy of freezing the degrees of freedom, with a more rigid and cautious gait pattern. Thus, interpretation of variability findings is not necessarily straightforward. In our study, although changes in variability were significant only in some directions and under some conditions, there was a general tendency for increased variability in all directions and under all conditions. This fits well with findings from studies showing higher gait variability and lower gait speed in older age groups [25,35]. We therefore suggest that our findings indicate decreased gait performance.

Variability in both ML and V directions changed significantly over two years for the dual task-condition. Dual task walking has been shown to affect gait performance, as cognitive/executive resources are taxed, leaving fewer attentional resources for the motor task [36]. While it has been shown that older adults perform worse during dual task than younger adults [37], we have found little information on changes in dual task performance over time. Our findings suggest that gait deterioration is more emphasized when automaticity is compromised than during unconstrained walking, highlighting the need for tests that are sufficiently challenging [14]. At the same time, there were no significant changes when walking across the uneven surface. We suggest that this task may have been relatively easy for the participants. Hiking and trekking in nature environments is a common pastime in Norway, and many of the participants may have been familiar with the challenges of walking on an uneven surface.

In this study, a follow-up period of two years was chosen. The choice of follow-up time is not trivial, and a longer follow-up period would likely have been associated with greater changes. In addition, the age at inclusion matters, as changes in physical functioning tend to accelerate with increasing age [1]. Still, we argue that the choice of two-years as a follow-up period balances the likelihood of changes taking place with risk of participants disappearing from the study.

The analyses were based on two walks of 6.5 m, and thus of two sets of approximately five to six consecutive strides. This is far less than what other authors have suggested for reliable measurements of variability [38]. It should be noted that these recommendations were based on footfall analysis. While we cannot rule out that our results would have been different over longer walking distances, we argue that the continuous nature of the acceleration signal, as opposed to only foot contacts, enables qualitatively different measurements than footfall analysis [13]. Previous studies using similar procedures and instrumentations as ours have shown acceptable to good reliability [39,40], and in a direct comparison with footfall analysis, the reliability of sensor-measured waveform gait variability was higher [41]. In comparison with other studies using similar metrics as ours but longer walking distances, comparable but slightly higher autocorrelation coefficients than the present study were found in all directions [18,20,21]. This could indicate that the participants in these studies reached a more steady state of walking and as such, that their gait was more consistent. It could also indicate that the participants in our study were frailer and had more balance problems during walking. However, we acknowledge the limitations with the number of strides used for analysis, and in further studies, sensor-measured waveform gait variability over different walking distances should be compared.

In summary, there was some increase in gait variability over the course of two years, in typically aging community-living older adults, that could not be explained by speed. For clinical purposes, we should expect an increase in gait variability with increasing age, and the change may be more pronounced during dual task-walking. Further, our findings imply how changes in gait variability may be interpreted: If changes exceed those reported in our study, there could be reasons to investigate for underlying pathological processes. However, further work should be undertaken to establish normative values of sensor-measured waveform gait variability for different age groups and for both sexes, to help in interpretation in clinical practice.

Limitations to this study include the low amount of strides that were used for analysis, a relatively small sample size, with a retention rate of 66%. Also, although no one was excluded from the study, we can not rule out that there were potential participants who were not reached who may have had difficulties in fulfilling the inclusion criteria. Thus generalizability is limited. Also, no exclusion criteria applied. This was deliberate, as the aim was to include typically aging persons. However, this also means that individuals with different diseases were included, and it is unclear how this may have impacted the results, and reproducibility in other studies may therefore be questioned. Further, testing took place in a lab, and so the participant’s performance may not be representative of how they perform in ecological environments. Still, we argue that a follow-up period of two years adds valuable information to the current knowledge about gait characteristics of older adults.

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