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Gait patterns in a community-dwelling population aged 50 years and older

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ABSTRACT

Poor gait is an important risk factor for falls and associated with higher morbidity and mortality. It is well established that older age is associated with worse gait, but it remains unclear at what age this association is first seen. Moreover, previous studies focused mainly on normal walking, but gait also encompasses turning and tandem walking. In a large study of community-dwelling middle-aged and elderly persons we investigated the association of age with gait, focusing on normal walking, turning and tandem walking. In 1500 persons aged 50 years and over, we measured gait using an electronic walkway. Participants performed normal walks, turning and a tandem walk. With principal components analysis of 30 variables we summarized gait into five known gait factors: *Rhythm*, *Variability*, *Phases*, *Pace* and *Base of Support*; and uncovered two novel gait factors: *Tandem* and *Turning*. The strongest associations with age were found for *Variability* (difference in *Z*-score −0.29 per 10 years increase (95% confidence interval: −0.34; −0.24)), *Phases* (−0.31 per 10 years (−0.36; −0.27)) and *Tandem* (−0.25 per 10 years (−0.30; −0.20)). Additionally, these factors already showed association with the youngest age groups, from 55 to 60 years of age and older. Our study shows that *Variability*, *Phases* and *Tandem* have the strongest association with age and are the earliest to demonstrate a poorer gait pattern with higher age. Future research should further investigate how these gait factors relate with gait-related diseases in their earliest stages.

1. Introduction

Proper gait is very important to function independently in a community. Not only is gait an important indicator of general health, but poor gait is also a predictor of adverse events, such as falls and mortality [1–6]. Various studies have shown that higher age is associated with worse gait [2,7–12]. With increasing life-expectancy, gait disturbances are therefore expected to become even more frequent [2].

Gait is a highly complex concept and can be studied using many different variables. These variables include simple measurements such as velocity, step length and step width, but also more complex measurements such as the variability within variables [7,8,13]. Consequently, the overlap across studies in variables used to study gait is limited. Ideally, gait is studied using as many variables as possible, but this would result in multiple testing as well as collinearity across variables.

In recent years, various studies have sought to solve this issue by principal components analysis (PCA). Using PCA on seven and eight variables, two studies summarized gait into three independent factors, referred to as *Pace*, *Rhythm* and *Variability* [3,4]. These factors were found to be associated with cognitive decline and risk of falls [3,4]. Another study expanded on this finding by including 15 additional gait variables in the PCA and uncovered two additional gait factors, which were named *Phases* and *Base of Support* [9]. Consecutively, the factors were found to be associated with age and sex [9].

The five gait factors described so far are all based on normal walking [3,4,9]. However, gait is a broader concept encompassing not only normal walking, but also turning and tandem (heel-to-toe) walking among others. Little is known about the effect of age on these aspects of gait. Furthermore, it is unknown whether these other aspects constitute additional gait factors or whether these can be captured by the previously described gait factors of normal walking.

Another consideration is that previous studies on aging and gait focused on elderly populations (60 years and over). The question

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remains whether the association between age and gait already starts at an earlier age. Investigating the earliest age-related changes in gait would provide novel insights into the normal aging progress and can serve as a basis to study pathologic gait disturbances.

The aim of our study was to investigate the association between age and gait in a population-based cohort study of middle-aged and elderly persons. We not only investigated normal walking, but also focused on turning and tandem walking. Similar to previous studies, we used PCA to summarize gait into a few independent factors.

2. Methods

2.1. Setting

The study was embedded in the Rotterdam Study, a prospective, population-based cohort study, originally started in 1990 [14]. The initial cohort was expanded in 2000 and 2005 and currently totals 14,926 persons. At study entry and during follow-up every 3–4 years, each participant undergoes a home interview and extensive physical examination at the research center. At these assessments height and weight are measured, and self-reported chronic diseases are recorded. From March 2009 onwards, gait assessment has been implemented in the core protocol. The current study comprises all participants that completed gait assessment until March 2011. All participants gave written informed consent. The study has been approved by the institutional Medical Ethics Committee.

2.2. Gait assessment

Gait was assessed with a 5.79 m long walkway (GAITRite Platinum; CIR systems, USA: 4.88 m active area; 120 Hz sampling rate) with pressure sensors, activated by the pressure of footfalls. This device is an accurate system to determine gait parameters [15–18].

Participants were asked to perform a standardized protocol consisting of three different types of walking: normal walk, turning and tandem walk. In the normal walk, participants walked over the walkway at their own pace. This walk was performed four times in both directions (eight recordings). In turning, participants walked over the walkway, turned halfway and returned to the starting position (one recording). In the tandem walk, participants walked tandem (heel-to-toe) over a line visible on the walkway (one recording). Examples of the three walks can be found in supplement 1.

In recordings of the normal and tandem walks, footsteps that did not fall entirely on the walkway at the start and the end were deleted. The first recording of the normal walk was treated as a practice walk and not included in the analyses. Recordings of individual walks were removed if instructions were not followed correctly or when fewer than four footprints were available for analyses. Spatiotemporal variables were calculated by the walkway software.

2.3. Study population

Between March 2009 and March 2011, we invited 1905 participants for gait assessment. Of these, 405 were excluded for various reasons: 196 participants were removed for technical reasons; 21 participants were excluded for use of walking aids, self-reported prosthesis or Parkinson's disease; 113 participants were excluded because of a too poor physical ability to walk; 41 participants were removed because they had fewer than 16 steps available for analyses, which lowers the validity of their gait parameters [19]; 14 participants refused to participate; nine participants refused to perform all walks; nine participants were removed because they did not follow instructions; and two participants did not perform the walks for other reasons.

After exclusion, 1500 participants were included in the analyses.

2.4. Statistical analysis

PCA with varimax rotation was performed on 30 variables to derive independent summarizing factors. A description of these 30 gait variables can be found in supplement 2. These were all variables that could be reliably measured using the GAITRite. Preliminary analysis did not suggest differences between legs; hence the mean of both legs was taken.

Factors were selected from the PCA if their eigenvalue was one or higher, signifying that each factor explains at least as much variance as a single variable. Communalities were calculated, reflecting the amount of variance in the variable explained by all factors. Variables were appointed to a certain factor if their correlation with the factor was $\geq$0.5. If necessary, factors were inverted so that lower values represent "worse" gait. The PCA yielded standardized factors (*Z*-scores) that were uncorrelated to each other.

Multiple linear regression analyses were used to determine the independent associations between demographics (age, sex, height and weight) and gait factors. Analyses involving tandem walk related variables were adjusted for the step length and step count in the tandem walk. We applied Bonferroni correction for 28 tests to correct for multiple testing. Additional adjustments were made for self-reported osteoarthritis and rheumatoid arthritis. We also calculated mean *Z*-scores of gait factors per 5-year age strata and per sex using ANOVA, adjusted for height and weight. Differences between sexes in the effects of age were tested using interaction terms (age $\times$ sex). All statistical analyses were performed using SPSS PASW version 17.0.2 for Windows.

3. Results

Characteristics of the study population are summarized in Table 1. Mean age was 68.8 years, and 817 (54.5%) were women. After summing all normal walks, an average of 41.75 (standard deviation (SD) 8.92) steps was available per participant. For turning an

Table 1
Population characteristics.

Characteristic	Total (n = 1500)	Men (n = 683)	Women (n = 817)
Age (yrs)	68.8 (10.1)	69.2 (10.3)	68.4 (9.9)
Height (cm)	168.5 (9.4)	175.7 (7.1)	162.6 (6.6)
Weight (kg)	78.0 (14.7)	85.1 (13.7)	72.1 (12.7)
Self-reported locomotor disorders			
Osteoarthritis (*n*)	343 (22.9%)	118 (17.3%)	225 (27.5%)
Rheumatoid arthritis (*n*)	46 (3.1%)	14 (2.0%)	32 (3.9%)

Values are mean (standard deviation) or numbers (%). *Abbreviations*: yrs, years; cm, centimeters; kg, kilograms; *n*, number.

average of 4.88 (SD 0.87) steps was available, and for the tandem walk an average of 12.99 (SD 2.76) steps was available.

The mean and SD of the variables used in the PCA are shown in Table 2. The PCA summarized these 30 variables into seven independent factors, explaining 87.3% of the total variance in gait (Table 2). In line with previous studies and based on the variables constituting these factors, we labeled these: *Rhythm*, *Variability*, *Phases*, *Pace*, *Tandem*, *Turning* and *Base of Support* [3,4,9]. High communalities ($\geq$0.60) were found for all original gait variables, except double step. All variables contributed to a factor with a correlation higher than 0.5 (Table 2). The correlations between each gait variable and each gait factor can be found in supplement 3.

Table 3 shows the multivariable adjusted associations of age, sex, height and weight with the gait factors. Higher age was significantly associated with a lower *Z*-score on all factors but *Rhythm*, which showed a higher *Z*-score with age. Strongest associations with age were found for *Phases*: difference in *Z*-score per 10 years increase in age −0.31 (95% confidence interval: −0.36; −0.27), *Variability*: −0.29 per 10 years (−0.34; −0.24) and *Tandem*: −0.25 per 10 years (−0.30; −0.20).

Fig. 1 shows the mean *Z*-scores across factors in 5-year age strata per sex. For both men and women, the earliest decrease in *Z*-score was seen for *Variability*, followed by *Tandem* and *Phases*: these three factors already showed a decrease in the earliest age-categories (55–60 years and older).

Women had a significantly lower *Z*-score on *Phases*, *Pace* and *Base of Support*, while men had a significantly lower *Z*-score on *Rhythm*. No significant interaction between age and sex was found for any of the gait factors ($p > 0.05$).

Larger height was associated with lower *Rhythm*, *Variability* and *Base of Support* and higher *Phases* and *Pace*. Higher weight was associated with lower *Phases* and *Turning*, and higher *Rhythm*, *Variability* and *Base of Support*.

After Bonferroni correction the associations of age with *Rhythm* and *Turning* were no longer significant. The associations of sex with *Phases* and weight with *Rhythm* and *Variability* did not survive Bonferroni correction either.

After adjustment for self-reported osteoarthritis and rheumatoid arthritis the associations remained similar: for example the association between age and *Variability* became −0.30 per 10 years (−0.35; −0.25), between sex and *Phases* became −0.14 (−0.27; −0.02) and between weight and *Turning* became −0.07 (−0.12; −0.03). For the other factors, too, the associations remained unchanged.

4. Discussion

Our study showed that gait assessed by normal walking, turning and tandem walking can be summarized in 7 independent factors, which are *Rhythm*, *Variability*, *Phases*, *Pace*, *Tandem*, *Turning*, and *Base of Support*. We found that higher age was associated with worse gait as reflected in *Variability*, *Phases*, *Pace*,

Table 2
Summarization of gait variables within independent gait factors.

Variable/factor	Percentage explained (%)[a]	Mean (SD)	Communality[b]	Correlation with factor[c]
Rhythm	21.5			
Single support time (s)		0.42 (0.03)	0.99	−0.96
Swing time (s)		0.42 (0.03)	0.99	−0.96
Step time (s)		0.55 (0.05)	0.99	−0.94
Stride time (s)		1.11 (0.10)	0.99	−0.94
Cadence (steps/min)		109.0 (9.3)	0.98	0.94
Stance time (s)		0.68 (0.07)	0.99	−0.84
Variability	20.0			
Stride length SD (cm)		4.71 (1.68)	0.83	−0.89
Step length SD (cm)		2.92 (0.96)	0.82	−0.87
Stride velocity SD (cm/s)		6.04 (1.92)	0.78	−0.86
Stride time SD (s)		0.03 (0.02)	0.86	−0.80
Step time SD (s)		0.02 (0.01)	0.88	−0.79
Stance time SD (s)		0.03 (0.01)	0.88	−0.79
Swing time SD (s)		0.02 (0.01)	0.82	−0.71
Single support time SD (s)		0.02 (0.01)	0.82	−0.71
Double support time SD (s)		0.02 (0.01)	0.60	−0.57
Phases	19.0			
Single support (%GC)		38.3 (1.6)	0.99	0.97
Swing (%GC)		38.3 (1.6)	0.99	0.97
Stance (%GC)		61.7 (1.6)	0.99	−0.97
Double support (%GC)		23.5 (3.2)	0.99	−0.96
Double support time (s)		0.26 (0.05)	0.99	−0.83
Pace	9.8			
Stride length (cm)		129.8 (17.0)	0.92	0.82
Step length (cm)		64.7 (8.5)	0.92	0.82
Velocity (cm/s)		118.0 (18.5)	0.92	0.69
Tandem	7.2			
Sum of feet surface (fraction)		0.34 (0.71)	0.87	−0.92
Sum of step distance (cm)		9.1 (17.0)	0.84	−0.90
Double step (*n*)		0.08 (0.32)	0.41	−0.63
Turning	6.1			
Turning step count (*n*)		4.88 (0.87)	0.87	−0.91
Turning time (s)		2.81 (0.62)	0.85	−0.85
Base of support	3.7			
Stride width SD (cm)		2.34 (0.76)	0.73	−0.79
Stride width (cm)		10.1 (4.0)	0.69	0.63
Total	87.3			

Abbreviations: SD, standard deviation; s, seconds; min, minutes; cm, centimeters; %GC, percent of the gait cycle time; *n*, number.
[a] The percentage explained is the amount of total variance in all gait variables explained by this factor.
[b] The communality is the amount of variance of the variable explained by all gait factors.
[c] Factors were inverted so that lower values represent "worse" gait. The numbers shown represent correlations after the inversion.

Table 3
Independent associations between the demographics and the gait factors.

Factor	Rhythm	Variability	Phases	Pace	Tandem[a]	Turning	Base of Support
Age (/10 yrs increase)	**0.06 (0.01; 0.10)**	**−0.29 (−0.34; −0.24)**	**−0.31 (−0.36; −0.27)**	**−0.14 (−0.18; −0.10)**	**−0.25 (−0.30; −0.20)**	**−0.08 (−0.13; −0.03)**	**−0.14 (−0.19; −0.08)**
Female vs. male	**0.52 (0.39; 0.65)**	−0.08 (−0.22; 0.06)	**−0.15 (−0.28; −0.03)**	**−0.42 (−0.54; −0.30)**	−0.12 (−0.26; 0.03)	−0.10 (−0.25; 0.04)	**−0.43 (−0.57; −0.28)**
Height (/10 cm increase)	**−0.27 (−0.35; −0.20)**	**−0.14 (−0.23; −0.06)**	**0.19 (0.12; 0.26)**	**0.42 (0.35; 0.49)**	−0.03 (−0.12; 0.05)	0.01 (−0.08; 0.10)	**−0.17 (−0.26; −0.09)**
Weight (/10 kg increase)	**0.05 (0.01; 0.08)**	**0.04 (0.00; 0.09)**	**−0.42 (−0.45; −0.38)**	0.01 (−0.02; 0.05)	0.00 (−0.04; 0.04)	**−0.08 (−0.12; −0.03)**	**0.09 (0.05; 0.13)**

Numbers represent changes in Z-score of the gait factors with their 95% confidence interval. A lower Z-score represents "worse" gait. Results in bold represent significant findings ($p < 0.05$).
Abbreviations: yrs, years; cm, centimeter; kg, kilogram.
[a] Additionally adjusted for step length and step count of the tandem walk.

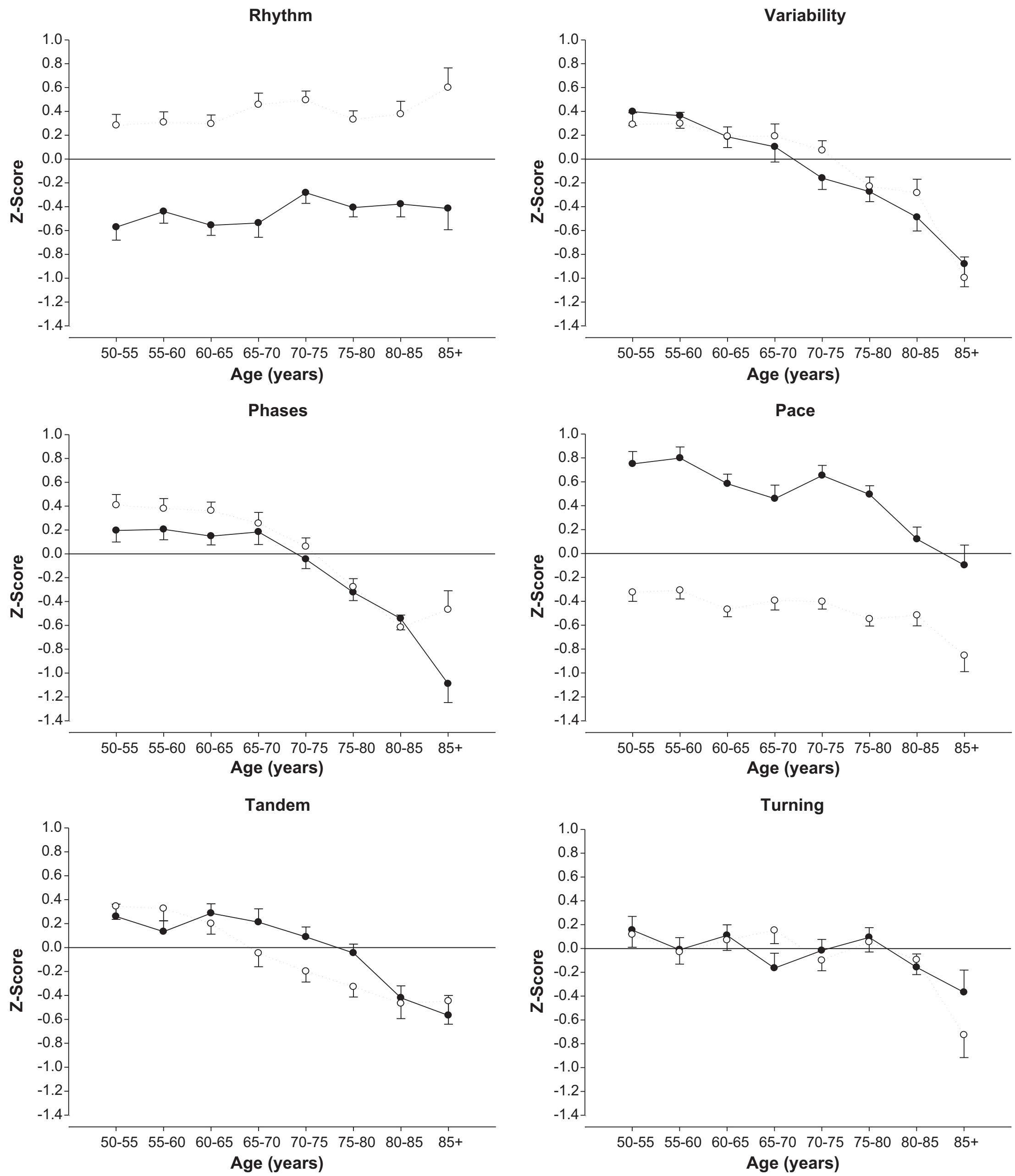
Tandem and *Base of Support*. The factor to show an association with the youngest age group was *Variability*, followed by *Tandem* and *Phases*. Between the sexes, women had poorer *Pace* and *Base of Support*, but better *Rhythm* than men.

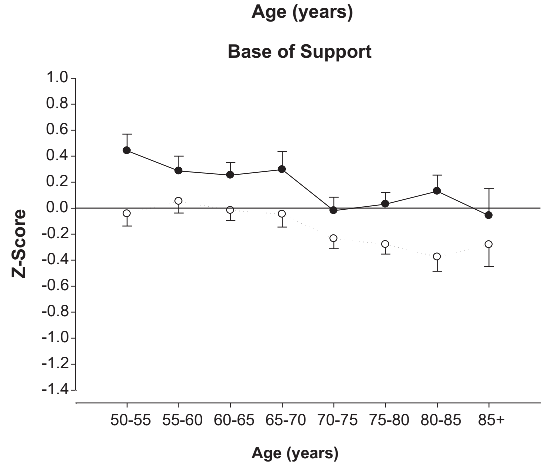
The strengths of our study include the population-based design, the large sample size, the relatively wide age-range, the many variables included and the different types of walk investigated. Our study also has some limitations. First, the cross-sectional design precludes the repeated assessment of age-related changes within participants. Second, participants only walked at their normal pace. Future studies should investigate whether results differ when walking at higher or lower velocity. Third, apart from normal walking, turning, and tandem walking, gait comprises other aspects which were not investigated, such as running, backward walking, and backward tandem walking. Inclusion of other walking conditions may reveal additional gait factors. Finally, our study sample was drawn from the general population and thus relatively healthy compared to clinic-based samples, both in terms of cognitive and physical health. This precluded the investigation of the effect of clinical disease on gait.

We found that gait can be summarized in seven independent factors. Of these, four factors were constituted by exactly the same variables as in another study summarizing gait [9]: *Rhythm*, representing most temporal variables of the normal walk; *Phases*, representing support time variables as percentages of the gait cycle and double support time; *Pace*, representing stride- and step length and velocity; and *Base of Support*, representing stride width and its variability. For *Variability*, which represents all variability variables excluding stride width variability, the same constituting variables were found as well, but we expanded this finding by showing that single support- and double support variability represent the same underlying factor. This supports the suggestion that all variability variables, except for stride width variability, represent the same underlying process [9]. The high correspondence of the gait factors we found for normal walking with those found in other studies demonstrates their robustness, and suggests that adding more gait variables to the factor analysis would not substantially change the composure of the already identified gait factors for normal walking [3,4,9]. Extending these findings, we identified two new factors representing additional walking conditions: *Tandem*, representing errors in the tandem walk and *Turning*, representing the number of turning steps and turning time. This result shows that investigating turning and tandem walking besides normal walking indeed yields additional information. Given that other studies have shown variables constituting *Turning* and *Tandem* to be associated with falls [20,21], this suggests that measuring *Turning* and *Tandem* may provide incremental value in assessing fall risk.

We found that higher age was associated with worse values on *Variability*, *Phases*, *Pace*, *Tandem* and *Base of Support*. This is in line with previous studies that found similar associations with individual variables constituting these factors [7,8,10,11]. A previous study using summarizing factors only found an association with age for *Phases* and *Pace*, but not for *Rhythm*, *Variability* and *Base of Support* [9]. This discrepancy could be due to less power, or the narrower age-range in that study. While other studies have found gait velocity to influence associations between age and gait [8,22], in our study gait velocity is part of a separate factor, *Pace*. This ensures that associations found for all other factors are largely independent from gait velocity.

We found *Variability*, *Phases* and *Tandem* to associate strongest with age and to be associated already with the youngest age groups. Interestingly, variables that constitute these factors have also been associated with falls [4–6,20]. This insinuates that assessing gait may aid in identifying those at the highest risk of





Age -range (yrs)	Nr. of men	Nr. of women
50 -55	73	93
55 -60	88	104
60 -65	117	144
65 -70	58	85
70 -75	105	137
75 -80	141	153
80 -85	74	71
85+	27	30

Fig. 1. The association between age and gait factors, in 5-year strata and by sex. A lower *Z*-score on a gait factor corresponds with worse gait. Black dots represent men and white dots represent women. Dots are height and weight adjusted means. Error bars represent the standard errors of the mean.

falls. Furthermore, the association of these factors with age and falls suggests that interventions of gait that are aimed at reducing the risk of falls should focus on improving *Variability*, *Phases* and *Tandem*. Furthermore, the difficulty in the visual assessment of especially *Variability* and *Phases*, suggests that electronic walkways for measuring gait may have a role in clinical practice to assess gait disturbances in their earliest stages.

Although higher age was also associated with worse *Pace* and *Base of Support*, these associations demonstrated smaller effect sizes and only showed differences at a higher age. The associations with age for *Rhythm* and *Turning* did not survive Bonferroni correction and should therefore be confirmed by future studies.

In our study, women had better *Rhythm*, but worse *Pace* and *Base of Support* compared to men. This suggests that women walk with quicker, but smaller steps, and have a narrower but more variable stride width. These findings are in line with other studies, which found similar associations for these factors or constituting variables [7,9,10]. We did not find differences between men and women in the association between age and gait.

The various factors together explain a high proportion of the total variance in gait. Each gait factor represents a different group of highly correlated variables. The factors are also independent from each other; ensuring that any association found for one factor has additional value over the associations found with other factors. Therefore, the use of gait factors has several advantages over the use of conventional gait variables. Previous studies have already demonstrated the use of gait factors in the assessment of various clinical outcomes, such as risk of falls and cognitive impairment [3,4]. One study found that worse *Phases* and, independently, *Variability* are associated with a higher risk of falls [4]. However, they did not recommend specific cut-off values to be used clinically. Furthermore, another study demonstrated that worse *Rhythm* and *Pace* may indicate a decline in global cognition, memory or executive functioning. Furthermore, they found that worse *Rhythm* and *Variability* are associated with an increased risk of dementia [3]. Additionally, many other morbidities appear to be associated with gait, such as sensory impairment, mobility disability and arterial stiffness [13,23,24]. Unraveling the associations between gait and these morbidities will aid in further understanding the aging process. Furthermore, assessment of gait may aid in the early detection or prediction of these morbidities. However, more research is needed before this can be materialized.

In conclusion, our study shows that gait can be summarized in seven independent factors: *Rhythm*, *Variability*, *Phases*, *Pace* and *Base of Support* representing normal walking, and *Turning* and *Tandem* originating from turning and tandem walking. This suggests that turning and tandem walking provide additional information on gait beyond normal walking. We found that higher age is associated with worse gait, with the strongest associations for *Variability*, *Phases* and *Tandem*. These were also the gait factors to show an association with the youngest age groups. Future studies should investigate the processes underlying this association between age and gait and investigate its association with the development of gait disorders and other morbidities.

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Conflict of interest statement

The authors declare that they have no conflict of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2012.09.005.

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