Master's thesis

NTNU
Norwegian University of Science and Technology

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The Effect of Age, Gender and Speed on Gait Strategies

Master's thesis in Movement Science
Supervisor: Beatrix Vereijken
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Abstract

Introduction: The elderly population has increased considerably in recent decades and continues to grow. To maintain functional independence in activities of daily life in older age, walking ability is of great importance. Due to natural age-related processes, balance control in gait can become progressively difficult, causing many elderly individuals to develop compensatory strategies to maintain stability. A vast amount of gait variables has been examined in literature, but each study only tends to focus on a few at the time. Comparisons between individuals and study populations are difficult because gait speed correlates to many different factors and gait variables. Principal component analysis (PCA) is a data reduction method, which has successfully compressed large data sets to smaller sets of principal components, with minimal information loss.

Aim: The purpose of the study was to explore the effects of age, gender and walking speed on gait strategies.

Methods: 20 older adults (10 men and 10 women) with mean age 78.9 years (SD: ± 2.94) and 20 younger adults (10 men and 10 women) with mean age 23.8 years (SD: ± 3.77) walked at three different instructed gait speeds (slow, preferred, and fast speeds) back and forth across an electronic walkway (GAITRite), twice for each gait instruction. We conducted PCA on 16 spatiotemporal variables on all three gait instructions and at a common, normalized speed (1.0 m/s) on different subgroups of the sample. We further compared them to an existing validated model and with other subgroups of the current sample in accordance with the study aim.

Results: The PCA compressed our original 16 variables into 3 and 4 components. Comparing age differences at normalized speed, the Rhythm and spatial variables was important for both groups. While temporal variability was important for the younger group, spatial variability was more prominent for the older. Asymmetry was more important at slow speed compared to normal and fast, while Rhythm was the main source of explained variance when walking at preferred speed. At fast speed, Postural Control and Pace-related variables were the largest contributor to variance.

Conclusions: We found that gait strategies are affected by age, gender and walking speed. Pace changes with advancing age, but not Rhythm. Older women are more dependent on Asymmetry than older men, and less on Rhythm. Pace was more important for fast speed, and Rhythm was more distinct for the older group at preferred speed, reflecting gait harmony and energy economy. At slow speed, the older adults were more likely to use an interlimb strategy (Asymmetry) than intralimb (Variability) which was more dominant at preferred and fast speeds.

Sammendrag

Introduksjon: Den eldre befolkningen har økt betraktelig de siste tiårene og den fortsetter å vokse. For å beholde selvstendighet i daglige aktiviteter når man blir eldre, er god gangfunksjon av stor betydning. På grunn av de naturlige aldersrelaterte prosessene kan balansekontroll i gange bli gradvis vanskeligere å oppnå, noe som gjør at mange eldre utvikler kompensasjonsstrategier for å opprettholde balansen. En stor mengde gangvariabler har blitt undersøkt i litteraturen men hver studie fokuserer typisk bare på noen få om gangen. Sammenligninger mellom individer og studiepopulasjoner er vanskelig, fordi ganghastighet korrelerer med mange forskjellige faktorer og gangvariabler, og deltagerne går vanligvis på selv-valgte hastigheter. Principal Component Analysis (PCA) er en metode for datareduksjon som hensiktsmessig har klart å redusere store datasett til mindre sett med komponenter, uten å miste informasjon.

Hensikt: Hensikten med studien var å utforske effekt av alder, kjønn og ganghastighet på gangstrategier.

Metoder: 20 eldre voksne (10 menn og 10 kvinner) med en gjennomsnittsalder på 78,9 år (SD: ± 2,94) og 20 yngre voksne (10 menn og 10 kvinner) med en gjennomsnittsalder 23,8 år (SD: ± 3,77) gikk i tre forskjellige instruerte ganghastigheter (sakte, normalt og rask) frem og tilbake over en elektronisk gangvei (GAITRite), to ganger for hver ganginstruksjon. Vi utførte PCA på 16 romvariabler på alle tre ganginstruksjonene og på en felles, normalisert hastighet (1,0 m/s) på ulike undergrupper av populasjonen. Videre sammenlignet vi dem med en eksisterende, validert modell og med andre undergrupper av gjeldende utvalg i samsvar med studiemålet.

Resultat: PCA reduserte de opprinnelige 16 variablene til 3 og 4 komponenter. Rhythm og romvariabler var viktige for både eldre og yngre da vi sammenlignet gruppene på normalisert hastighet. Mens temporal variabilitet var viktig for den yngre gruppen, var variabilitet i romvariabler mer fremtredende for de eldre. Asymmetry var mer utslagsgivende ved sakte gange sammenlignet med normal og rask gange, mens Rhythm forklarte mest av den totale variasjonen i datasettet når de eldre gikk i normal hastighet. I rask gange var Postural Control og Pace-relaterte variabler den største bidragsyteren til den totale variansen.

Konklusjoner: Våre resultater viste at gangstrategier blir påvirket av alder, kjønn og ganghastighet. Pace endres med alderen, men ikke Rhythm. Eldre kvinner var mer avhengige av Asymmetry enn eldre menn, men mindre avhengig av Rhythm. Pace var viktig for de eldre ved rask gange på normalisert hastighet, og Rhythm var mer fremtredende i normal ganghastighet, som kan reflektere gangharmoni og energiøkonomi. I sakte gange foretrakk de eldre en interlimb-strategi (Asymmetry) framfor en intralimb-strategi (Variability), som var mer dominant ved normal og rask gange.

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Abbreviations/symbols

NTNU	Norges teknisk-naturvitenskapelige universitet
COM	Center of Mass
EMG	Electromyography
FAP	Functional Ambulation Profile
PCA	Principal Component Analysis
BMI	Body Mass Index
FES	Falls Efficacy Scale
MMSE	Mini Mental State Examination
SL	Step Length
SW	Step Width
ST	Step Time
StaT	Stance Time
SS	Single Support

SVel	Step Velocity
SL_Var	Step Length Variability
SW_Var	Step Width Variability
ST_Var	Step Time Variability
StaT_Var	Stance Time Variability
SS_Var	Single Support Variability
ST_Var	Step Velocity Variability
SL_As	Step Length Asymmetry
ST_As	Step Time Asymmetry
StaT_As	Stance Time Asymmetry
SS_As	Single Support Asymmetry
REK	Regionale komiteer for medisinsk og helsefaglig forskningsetikk
NSD	Norsk senter for forskningsdata
SF-36	Short form-36

1 Introduction

1.1 Gait in older age

In most countries, life expectancy in the elderly has increased significantly over the past decades, leading to a larger proportion of older people in the total population. The global count of people over 65 years of age was 703 million in 2019 and is expected to reach 1.5 billion by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2019). With a growing elderly population comes an increasing number of age-related issues, including reduced mobility, falls and a decline in functional abilities due to falls (Alexander, 1996; Alexander, 1992). Even when falls do not result in fractures or other injuries, elderly can experience fear and depression, leading to increased fall risk, less physical activity, immobilization and even institutionalization (O'Loughlin et al., 1993; Demura et al., 2008).

With the progressive expansion of the group of older adults, it is of great interest to the public that self-care and functional ability are maintained at older age with the aim of avoiding hospitalization and institutionalization (Guralnik et al, 1996). Walking ability is important in this context as it is essential to carry out activities of daily living, to maintain social interactions, and to ensure quality of life (Guralnik et al., 1995; Iezzoni et al., 2000). One of the main aspects of walking is balance control, defined by MacKinnon & Winter (1993) as a person`s ability to stabilize the body center of mass within the borders of the feet. While this is appropriate for balance control in stance, it fails to describe balance control in dynamic motor tasks where COM can move outside the boundaries of support without leading to a fall. When we walk, the center of gravity shifts forward towards the medial line of the stance leg, outside the base of support. (Tang & Woollacott, 2004). This is only accomplished by initiating a forward fall which in turn is prevented by placing the swing foot securely and recovering balance at ground contact (Winter, 1995). Shkuratova et al. (2004) defined balance control during walking as the skill to walk safely by successfully incorporating postural adjustments with movement strategies.

Many individuals experience problems controlling their balance as they age (Helbostad & Moe-Nilssen, 2003). For many, this deterioration is partly caused by the natural process of aging which involves physical and neurological declines (Prince et al., 1997). Some examples of these declines include a decrease in muscular force production, muscle atrophy and increased fat mass (Larsson & Ramamurthy, 2000), reduced joint range of motion (Walker et al., 1984), impaired vision (Helbostad et al., 2009), sensorimotor impairments, including reduced sense of vibration and proprioception (Tang & Woollacott, 2004), and slower reaction times (Overstall, 2004). Because of these biological aging processes, balance control during walking can become gradually more challenging with advancing age and consequently increase risk of falls (Shkuratova et al., 2004). Therefore, some elderly may develop compensation strategies to maintain gait stability. Older individuals tend to prefer a slower gait speed than younger individuals (Kang & Dingwell, 2008), resulting in shorter strides and steps, decreased swing phases and prolonged time in the single and double stance phases for the elderly (Laufer, 2006; Craik, 1990; Menz et al., 2003; Shkuratova et al., 2004). Additionally, slower gait speed in combination with shorter step lengths (Maki, 1997) and increased step timing variability (Menz et al., 2003) or increased stride width and double support durations in older gait (Gabell & Nayak, 1984) generally symbolize adaption mechanisms for reduced balance control.

Few studies have examined gait parameters in older versus younger age in both men and women to see whether their walking patterns are similar or differ from one another with advancing age. One population-based study revealed speed and step length reductions, followed by an increase in double support time with age in both sexes (Shumway-Cook et al., 2007), whereas other studies found these associations to be more pronounced for the female subjects only (Callisaya et al., 2008; Blanke & Hageman, 1989).

Several studies have shown that gait patterns are affected by walking speed and that ground reaction forces, biomechanical parameters and spatiotemporal gait variables seem to be speed dependent (Fukuchi et al., 2019). With respect to spatiotemporal parameters, Fukuchi and colleagues (2019) reported increases in cadence, stride- and step lengths with increasing gait speed, accompanied by decreased time spent in stance phases. The opposite was observed for slow walking. Furthermore, healthy young adults show greater variability in spatio-temporal gait parameters at slower walking speeds (Kang & Dingwell, 2008) than at preferred walking speeds. It has been shown previously that preferred and maximum gait speeds are correlated with height/leg length (Hof, 1996), age and leg strength, with slower gait being more common in smaller, older people with less leg muscle strength (Bohannon, 1997).

Most studies on gait use self-selected walking speeds, usually with different speed instructions (for example slow, normal, and/or fast). The disadvantage of this approach is that making comparisons between individuals or groups of individuals becomes problematic, since that would require everyone to walk at the same speed (Kang & Dingwell, 2008). When walking at different speeds, the results can thus be confounded by these differences in gait speed. On the other hand, walking at a fixed speed, for example on a treadmill, affects gait characteristics as well, since it is not free gait (Helbostad & Moe-Nilssen, 2003). As a potential solution, Helbostad and Moe-Nilssen (2003) demonstrated that curvilinear interpolation allows for comparison of speed-dependent gait parameters using a normalized-speed regression model. This model allows the participant to walk at different self-chosen speeds, without hampering the results when comparisons between participants or groups are made, as this comparison can be done at a normalized gait speed that is the same for all participants.

Velocity, step length and cadence are the most frequently reported basic gait parameters (Öberg et al., 1993). Even though most studies focus on a limited number of variables, the large body of gait research provides a diverse set of variables that have been documented over the years. These range from basic spatial and temporal footfall parameters to COM acceleration, EMG recordings and Functional Ambulation Profile (FAP) scores (Callisaya et al., 2008; Titianova et al., 2004). Only a few studies have examined the association between spatial and temporal footfall variables such as step width and double support duration (Blanke & Hageman, 1989; Callisaya et al., 2008; Gabell & Nayak, 1984; Hageman & Blanke, 1986; Helbostad & Moe-Nilssen, 2003) and even fewer have investigated potential differences in gait characteristics across age and gender.

1.2 Studying gait strategies

One promising method to investigate the relationship between many variables, or gait strategies, is Principal Component Analysis (PCA). PCA is a method designed to reduce a large data set with a high number of variables into a smaller data set with only a few independent variables or components. Despite being a powerful method to reduce a large number of various spatiotemporal gait variables to a handful of independent components, PCA has been used to study gait patterns in a few studies only. Sadeghi and colleagues (1997), for instance, studied peak power and biomechanical energy for the lower extremity joints in all three anatomical planes – totaling 48 parameters for each limb (Sadeghi et al., 1997), which were reduced to four independent components that together explained 60% of the variance. Similarly, Deluzio and partners (1997) performed measurements on knee bone-to-bone forces, knee net reaction forces and knee angles measured in various planes (Deluzio et al., 1997) to develop a PCA model for gait patterns of a normal population compared to a group of patients with osteoarthritis. PCA has also been used successfully on other gait parameters such as EMG recordings of muscular activity of various muscles in the lower limb (Shiavi & Griffin, 1981), and on various limb and body angles for both upper and lower extremities (Das et al., 2005). Despite these promising results, only a handful of studies have applied PCA on spatial and temporal footfall parameters to identify gait components.

One of the earliest attempts comes from Verghese and colleagues (2007) who conducted PCA on up to eight different gait parameters obtained from older adults walking in a straight line, condensing them to three independent components which they identified as Pace, Rhythm and Variability. Based on these findings, Hollman and colleagues (2011) used PCA to summarize 23 variables collected from a population of men and women above 70 years into five primary components. They described these components as Rhythm, Phase, Variability, Pace and Base of Support. In addition to walking straight, Verlinden and colleagues (2013) included additional gait variations such as turning and walking heel to heel in their study, totaling 30 variables in total. This resulted in the same five components reported by Hollman plus two additional components, Turning and Tandem (Verlinden et al., 2013).

Looking at 16 spatio-temporal gait characteristics, Lord, and coworkers (2013) proposed a model with Pace, Rhythm, and Variability domains, as in the models of Verghese and Hollman. In addition, they introduced two new gait domains: Asymmetry, loading on asymmetry data, and Postural Control, loading on Step Width Asymmetry and Step Length Asymmetry (Lord et al, 2013).

Although many earlier studies on gait in elderly included both women and men, typically walking at their preferred gait speed, no studies have examined the differences in the number and content of gait components between men and women, and thereby fail to consider the potential impact of gender on gait strategies. Furthermore, we know that gait parameters change as people grow older, but an evaluation of the effect of age on gait strategies by comparing younger and older people using PCA has not yet been conducted. Similarly, the bulk of studies on gait in older adults have been limited to one or two different walking speeds, without investigating whether gait strategies change with faster or slower gait speeds. As a result, knowledge about the effects of gender, age, and gait speed on gait strategies is currently lacking in the literature.

The purpose of the present study was therefore to investigate the effects of age, gender, and walking speed on gait strategies, as expressed by the relationship between temporal and spatial footfall parameters of gait. We propose the following hypotheses:

- Older and younger adults have different gait strategies at normalized speed
- Older women and men have different gait strategies at normalized speed
- Older adults use different gait strategies at slow speed than they do at preferred speed and fast speed
- Older adults use different gait strategies at fast speed than they do at slow speed and preferred speed

2 Methods

2.1 Design

The present study had a cross-sectional design with a convenience sample of 20 young and 20 older adults walking at three different speed instructions. The young adults were tested at the former HiST, now part of NTNU. The data on the older adults were collected in a previous study by Karin Hesseberg at NTNU/St.Olavs hospital (Hesseberg, 2007).

2.2 Participants

The older sample consisted of 10 women (79.1 years ± 3.07) and 10 men (78.6 years ± 2.95). To be included in the study, participants had to have normal vision for their age and being capable of walking at least 10 meters without walking aids or assistance. Exclusion criteria were cataract surgery within the last three months or stroke the last 6 months prior to the study. They were also excluded if they had undergone hip or knee surgery or if they scored below 20/30 on the Mini Mental State test (Hesseberg, 2007).

The younger sample consisted of 10 women (22.5 years ± 2.17) and 10 men (25.0 years ± 4.67) recruited from HiST. To be included in the younger group, participants had to be between 20 and 35 years of age. Participants were not allowed to enroll in the project if they had undergone hip or knee surgery the past year, took balance-influencing medication or suffered from other illnesses that impaired balance.

2.3 Gaitrite electronic mat

Measurements of the temporal (timing) and spatial (distance) gait characteristics were obtained using the GAITRite System (CIR Systems Inc. Havertown, PA 19083). The GAITRite is a walkway with surface-encapsulated pressure sensors that detect and analyze footprints electronically when participants walk across the carpet (GAITRite office manager handbook). The pressure sensors are arranged in a grid pattern with a total of 16,128 sensors placed 12.7 mm apart over a 4.88 meter walkway. The GaitRITE samples at a frequency of 80 Hz and localizes and records the relative arrangement of each footfall as a function of time. A personal computer with GAITRite Software version 3.8 installed was used during the data processing and storing.

2.4 Procedure

Before data collection began, participants received an introduction to the project and had the opportunity to ask questions. After giving informed consent, background variables were collected. Participants were then instructed to walk back and forth across the walkway at three different speeds. First, they were asked to "walk slowly as if you are strolling around". After having crossed the mat to the other end, they were instructed to stop and turn before returning over the mat walking at the same instructed speed. The same procedure was repeated for the two other instructed speeds: "walk at your normal, preferred speed" and "walk as fast as you can safely walk". The gait measures were averaged both trials at the same speed instruction.

The order of walking speeds was the same for all participants, namely slow, normal, and fast. All participants wore their own shoes during testing. The entire procedure took about 30 minutes to complete.

2.5 Measures

The background variables collected for the younger group were Gender (male/female), Date of birth (day/month/year), Height (in centimeters), Weight (in kilos), Vision (normal or corrected to normal by glasses or contact lenses), and Training during the last year (how often, intensity, duration).

The background variables for the older group included Gender (male/female), Age (in years), Height (in centimeters), Body Mass Index (BMI), Physical and Mental Health scales, Falls Efficacy scale (FES), Mini Mental State Examination (MMSE) and the Physical Functioning scale of the 36-Item Short-Form Health Survey. Vestibular function was evaluated by a geriatrician, use of glasses and examination of vision was performed in accordance with the Physiological Profile Assessment (see Hesseberg, 2007, for details).

All gait variables obtained from the GaitRITE system were recorded for both left and right feet. In the analysis, six spatiotemporal variables (averaged across both feet), six variability characteristics and four asymmetry characteristics were used.

Spatial (distance) parameters included in the study were Step Length, measured as the distance between the heel centers of current footprint and the previous footprint of the opposite foot (cm), and Step Width as the horizontal distance (cm) from the heel center of one footprint to the progression line of the opposite foot (GaitRITE CIR Systems Inc, 2006).

Temporal (time) parameters included Step Time, defined as the time elapsed from heel strike of one foot to heel strike of the opposite foot (in seconds), Stance Time, measured as the time between heel contact and toe-off of the same foot (in seconds), Single Support, obtained as the time between toe-off of the other foot to heel contact of the next footfall of the same foot (in seconds) and Step Velocity, calculated by dividing Step Length by Step Time. Gait speed was calculated by dividing the distance traveled by travel time.

Variability was calculated for the following variables: Step Length Variability, Step Width Variability, Step Time Variability, Stance Time Variability, Single Support Variability and Step Velocity Variability.

Variability characteristics were established by first calculating the standard deviations of steps made by the left and right feet separately, and then combined by taking the square root of the average variance of the left and right steps, as shown in Equation 1:

$$\boldsymbol{SD_{Left\&Right}} = \sqrt{\frac{(\boldsymbol{Variance_{Left\,steps}} + \boldsymbol{Variance_{Right\,steps}})}{\mathbf{2}}} \quad \textbf{(Equation 2.1)}$$

Asymmetry was calculated for the following variables: Step Length Asymmetry, Step Time Asymmetry, Stance Time Asymmetry and Single Support Asymmetry. The definition of gait asymmetry used in this study is that from Yogev et al. (2007) where values close to 0 indicate symmetry, while the degree of asymmetry increases with higher values. Asymmetry characteristics were calculated according to this formula:

$$\textit{Gait Asymmetry} = 100 * \left| ln\frac{Left}{Right} \right| \quad \textbf{(Equation 2.2)}$$

2.6 Normalization of gait variables

To compare the walking patterns of participants walking at different self-controlled speeds and to avoid possible confounding effects of gait speed differences between participants, all gait variables were normalized to a standardized speed of 1.0 m/s which has also been used in previous studies (Helbostad & Moe-Nilssen, 2003).

This could be done since we had two trials per participant at each of three different instructed speeds. The curvilinear relationship between each parameter and gait speed was calculated for each participant, and by interpolation we could estimate values for each parameter at the chosen speed of 1.0 m/s. For the variability and Asymmetry variables, in cases where only two trials and hence only two data points were available, linear interpolation was used. Where 3-6 data points were available, a polynomial fit was chosen if the linear fit and the polynomial fit were within 10% accuracy of each other, and with more than 10% deviation, the linear fit was selected. To avoid extrapolation in cases where interpolation was impossible (for example when participants walked faster than 1.0 m/s at all three gait instructions in all six gait trials), the data points from the gait trial closest to 1.0 m/s were obtained. The Step Velocity value reveals the speed at which the data points were obtained.

Figure 2.1 shows the linear and polynomial relationships between Step Length (cm) and gait speed (m/s) for one participant.

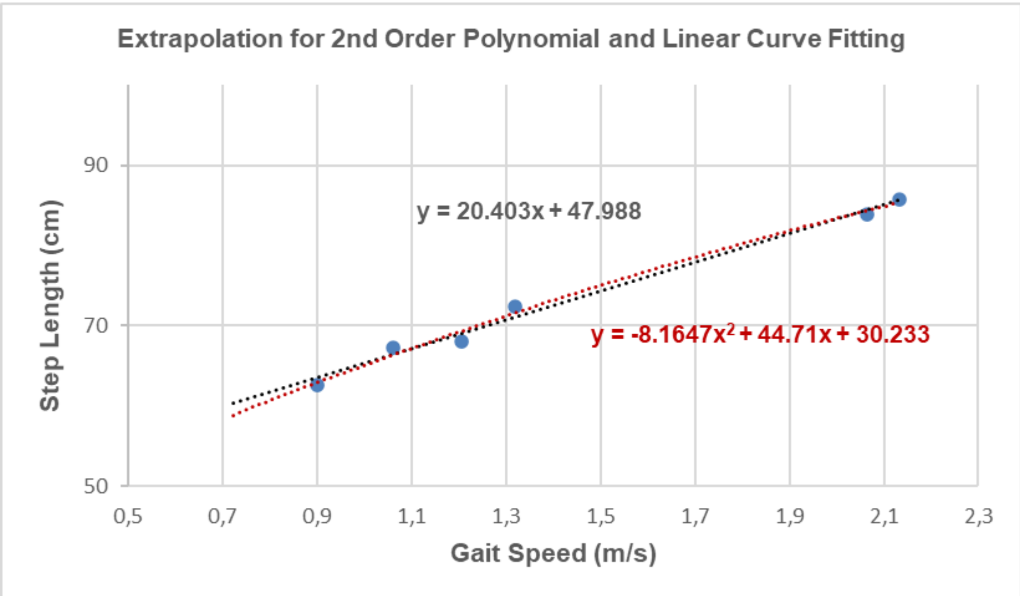

Figure 2.1: The 2nd order polynomial and linear relationships between step length and gait speed for one participant, demonstrated in a scatterplot.

2.7 Data analysis

The data collected by the GAITRite system were stored as ASCII-files and converted to Microsoft Office Excel. Incomplete footfalls in the beginning and the end stage of each trial were deleted. Data analysis was performed in Excel and SPSS 14.0 and 27.0.0.0 for Windows.

2.8 Statistical analysis

Descriptive statistics were computed for all gait variables at all speeds and for both age groups and genders. To compare basic descriptive parameters, a two-way MANOVA Group x Gender was applied for gender and group differences. To compare background variables between genders within the older group, independent t-tests were applied.

A 3-way mixed model/repeated measures ANOVA was applied to explore gender, age, and speed instruction differences, as well as interactions between these three factors. Significant effects of speed Instruction were followed up by post-hoc comparisons using Bonferroni corrections. For all statistical tests, significance was set at $p<0.05$.

Factor Analysis using Exploratory Principal Component analysis with Varimax rotation was performed on all gait variables at all speeds to identify possible clusters of variables. Factors were extracted when the minimum eigenvalue reached 0.7. Scree plots were examined to determine the number of components extracted, and factor and item loadings were investigated to clarify the importance of each variable within a factor. A variable was assigned to a factor if it had a minimal rotated factor loading of $|0.4|$. Components were also controlled for possible variable cross-loadings.

2.9 Ethical considerations

The participants were informed that study participation was voluntary and that they could decline to enroll in the project or withdraw at any time without having to explain why and without penalties. All participants signed an informed consent prior to data collection.

The participants were informed that all data would be treated confidentially and stored anonymously in a database. The data sampling was carried out according to the Declaration in Helsinki. This study was approved by the Regional Committee for Medical Research Ethics (REK) in Health Region IV and the Norwegian Social Science Data Services (NSD).

3 Results

Twenty young adults (ten women, ten men) with an average age of 23.8 years and twenty older adults (ten women, ten men) with an average age of 78.9 years were enlisted in the study. The older group had significantly higher BMI than the younger group, $t(38)=-2.49$, $p<0.05$. The younger group was on average slightly taller than the older group, but this difference did not reach significance ($p>0.05$). The sample characteristics for each age group are presented in Table 3-1.

Table 3-1: Age, height, and BMI (mean, SD) per age group; p-values refer to the differences in age, height, and BMI between the younger and older groups.

	Group	Mean	Std. Deviation	N	p-value
Age (years)	Younger	23.8	3.768	20	0.001
	Older	78.9	2.943	20	
Height (cm)	Younger	172.4	10.409	20	0.119
	Older	167.3	9.572	20	
BMI (kg/m^2)	Younger	24.8	3.543	20	0.017
	Older	27.5	3.371	20	

p<.05 was selected as the minimum criterion for significance.

3.1 Gender differences in the older group

The older males were significantly stronger in the lower body than the older women. Quadriceps Muscle strength in the older women was on average 55.2% of that in the men ($t(18)=-5.10$, $p<.001$), while Hamstring- and Dorsiflexor strength were 54.9% ($t(18)=-4.60$, $p<.001$), and 68.5% ($t(18)=-4.68$, $p<.001$), of that in the older men, respectively. The men also reported significantly higher scores on the Physical Functioning subscale of the SF-36 than the older women, $t(13.86)=-2.98$, $p<.001$, indicating a better Physical functioning for the men. The older women scored higher on the FES-scale and the MMSE-scale, but these differences were not significant. The older men were significantly taller than the older women, $t(18)=-5.51$, $p<.001$, and the women had a larger BMI than the men, but this difference did not reach significance.

3.2 Walking speed

All 40 participants walked back and forth across the gait mat at three different speed instructions (preferred, fast and slow), resulting in six gait trials for each participant. The mean walking speed for each age group for all three speed instructions is presented in Table 3-2.

Table 3-2: Walking speed (mean, SD, in m/s) per age group, gender and speed instruction.

Instruction	Group	Gender	Mean	Std. Deviation
Preferred speed	Younger	Female	1.44	0.157
		Male	1.27	0.104
	Older	Female	0.97	0.152
		Male	1.12	0.200
Fast speed	Younger	Female	2.04	0.199
		Male	2.05	0.224
	Older	Female	1.32	0.250
		Male	1.52	0.232
Slow speed	Younger	Female	1.10	0.283
		Male	0.85	0.226
	Older	Female	0.68	0.106
		Male	0.70	0.176

A three way ANOVA Age x Gender x Instruction on Walking speed indicated a main effect of Instruction, $F(2,35) = 204.94$, $p<.001$. Post-hoc comparisons with Bonferroni corrections indicated that gait speed at all three Instructions were significantly different from each other, all p's < 0.001. There was also a significant main effect of Group, $F(1,36)=66.91$, $p<.001$, indicating that overall, younger adults walked faster than older adults across instructions. In addition, there was a significant interaction between Instruction and Group, $F(2,35)=16.82$, $p<.001$, indicating that especially younger adults increased speed when walking fast, and a significant interaction between Group and Gender, $F(1,36)=6.86$, $p<.005$, indicating that the difference in fast walking speed between younger women and older women was larger than the difference in fast walking speed between younger men and older men. The remaining interactions were not significant.

The average walking speeds for both trials at all three gait instructions for all participants and they are shown in Figure 3.1. The red line indicates the chosen Normalized Velocity (1.0 m/s).

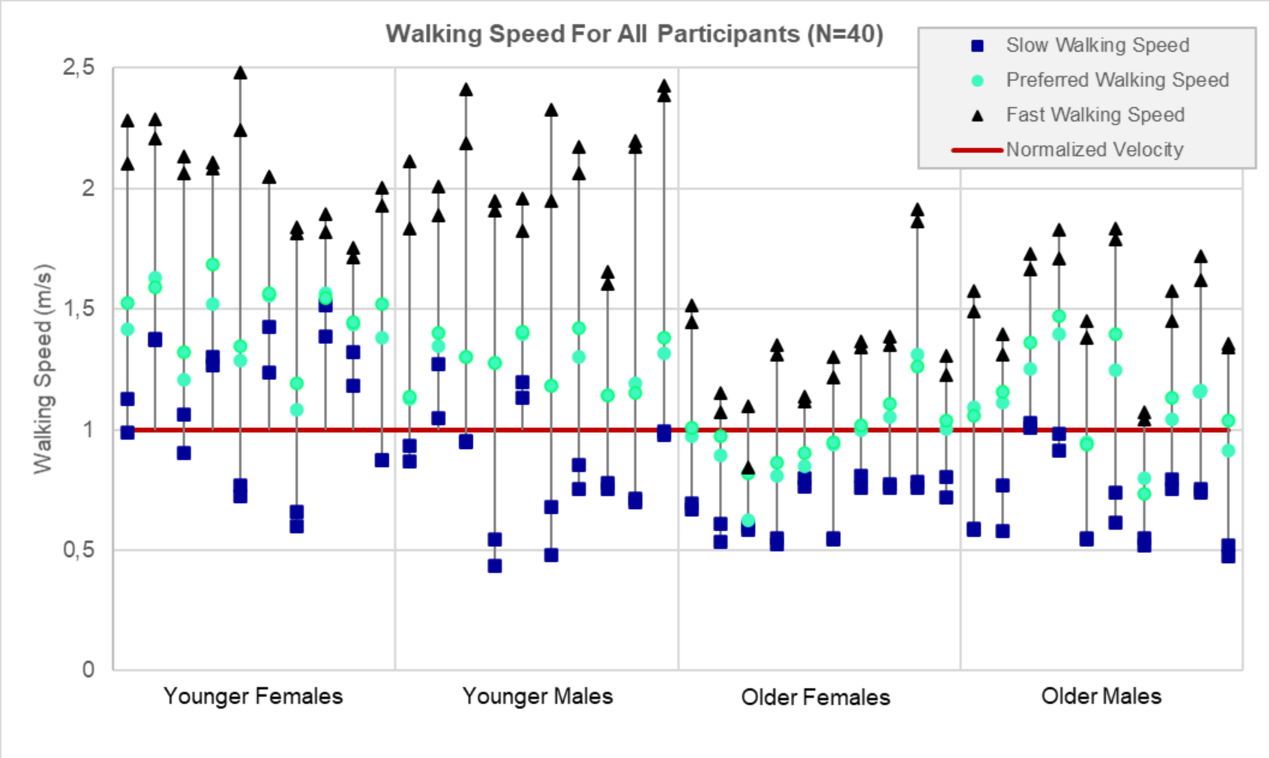

Figure 3.1: Walking speed for all participants for both trials at each instructed speed (Slow, Preferred, Fast).

3.3 Gait characteristics

In order to be able to compare gait characteristics across the two groups, despite older and younger adults walking at different speeds, we normalized all gait variables to 1.0 m/s. The normalized value for each gait variable for each participant was calculated using curvilinear interpolation where sufficient data points were available (see Methods). The gait characteristics at normalized speed for all four groups of participants (young women, young men, older women and older men) are shown in Table 3-3.

Table 3-3: Gait characteristics at normalized speed for younger and older women and men.

	Younger						Older					
	Women			Men			Women			Men		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Mean spatiotemporal characteristics												
Step Velocity (cm/s)	114.57	16.34	100.05-138.85	101.99	4.30	100.05-113.35	100.12	0.16	99.76-100.3	100.24	0.28	100-100.95
Step Length (cm)	63.45	4.82	54.09-71.49	64.36	4.39	59.9-71.03	58.11	3.74	51.97-62.81	64.61	3.53	58.66-69.51
Step Width (cm)	64.47	4.76	55.39-72.45	66.19	4.52	61.85-73.46	59.01	3.60	52.67-63.72	66.30	3.47	61.27-71.47
Step Time (s)	0.63	0.04	0.55-0.67	0.65	0.05	0.59-0.74	0.58	0.04	0.52-0.64	0.65	0.04	0.58-0.7
Swing Time (s)	0.46	0.05	0.36-0.55	0.45	0.04	0.39-0.52	0.41	0.03	0.36-0.46	0.46	0.04	0.38-0.51
Stance Time (s)	0.80	0.05	0.71-0.88	0.85	0.06	0.78-0.96	0.75	0.06	0.62-0.81	0.83	0.04	0.77-0.91
Variability characteristics												
Step Velocity (cm/s)	5.02	1.50	3.33-8.85	5.35	2.12	2.84-10.59	4.84	1.30	3.28-7.87	5.05	1.61	2.79-8.59
Step Length (cm)	1.57	0.37	0.83-2.21	2.08	0.77	1.16-3.27	2.25	0.51	1.57-3.53	2.23	0.62	1.49-3.13
Step Width (cm)	1.50	0.41	0.91-2.12	1.93	0.61	1.11-2.93	2.20	0.47	1.48-3.14	2.16	0.53	1.35-2.89
Step Time (s)	0.02	0.01	0.01-0.03	0.02	0.02	0.01-0.07	0.02	0.01	0.01-0.04	0.02	0.01	0.02-0.04
Swing Time (s)	0.01	0.01	0-0.02	0.02	0.01	0-0.05	0.02	0.01	0.01-0.03	0.02	0.01	0.01-0.03
Stance Time (s)	0.02	0.01	0.01-0.04	0.02	0.01	0.01-0.05	0.03	0.02	0.02-0.07	0.03	0.01	0.02-0.04
Asymmetry characteristics												
Step Length (cm)	2.89	1.50	0.35-5.76	5.06	2.19	2.37-8.02	4.06	1.45	2.47-6.63	6.24	4.37	2.11-15.64
Step Time (s)	2.08	1.38	0.06-4.09	3.65	2.64	0.94-9.49	3.72	1.89	1.32-6.35	3.65	1.90	1.32-7.18
Swing Time (s)	3.08	1.88	0-6.63	3.42	2.27	1.3-7.95	4.39	2.33	1.57-9.42	4.63	1.40	2.86-7.12
Stance Time (s)	1.71	0.94	0.76-3.41	1.90	1.33	0.41-4.19	2.94	2.28	1.14-9.15	2.05	0.74	0.77-2.94

A two-way MANOVA Group x Gender on all 16 normalized gait parameters indicated several significant main effects of Group. The younger group walked with a larger Step Velocity ($F(1,36)=9.19$ $p<.004$), a greater Step Width ($F(1,36)=4.22$ $p<.047$), and with more time spent in Stance ($F(1,36)=4.15$ $p<.049$) than the older group. The older group walked with larger Step Length Variability ($F(1,36)=5.06$ $p<.031$) and Step Width Variability ($F(1,36)=8.18$ $p<.007$) than the younger group.

There were also a several significant main effects of Gender. Women walked with a larger Step Velocity ($F(1,36)=5.43$ $p<.025$), but had smaller Step Lengths ($F(1,36)=7.97$ $p<.008$) and Step Widths ($F(1,36)=11.94$ $p<.001$) than men. The men walked with longer Step Time ($F(1,36)=10.41$ $p<.003$), spent more time in Stance ($F(1,36)=12.86$ $p<.001$) and walked with increased variability in Single Support ($F(1,36)=5.83$ $p<.021$), and with larger Step Length Asymmetry than women ($F(1,36)=6.72$ $p<.014$).

There were also several significant Group x Gender interactions. The younger women walked with a higher Step Velocity ($F(1,36)=5.66$ $p<.023$) than the other groups. The older women also had a significantly shorter step Length ($F(1,36)=4.53$ $p<.040$), narrower Step Width ($F(1,36)=4.55$ $p<.040$) and spent less time in Single Support ($F(1,36)=4.84$ $p<.034$) than the other groups. Interactions for the other parameters did not reach significance (all p`s>0.05).

3.4 Gait strategies

To be able to investigate relationships between age, gender, and walking speed on gait strategies, it was important to find the major patterns in the data without losing important information in the process, and to this end, we used Principled Component Analysis (PCA). PCA is a method to simplify complex and large data sets by reducing dimensionality and minimizing information loss by retaining most of the variance and thus making the data easier to interpret. PCA was conducted on the same 16 variables that were used by Lord et al. (2013).

3.5 Validation of the model

To be able to compare our data set with that used in Lord et al. (2013), the PCA results of older adults walking at preferred speed are shown in Table 3-4.

Table 3-4: PCA variable distribution for the older group at preferred walking speed.

	Preferred walking speed			
	PC1	PC2	PC3	PC4
Older	**ST**	**SL_Var**	**SL**	**StaT_Var**
	StaT	**SW_Var**	**SW**	**SS_As**
	SS	**SVel_Var**	SVel	**StaT_As**
	ST_Var	-SL_As		ST_As
	SS_Var	(ST_As)		
	(SVel)			
% explained variance	31.44	23.12	19.90	9.20

StaT=Stance Time; SW=Step Width; SL=Step Length; ST=Step Time; SS=Single Support; SVel= Step Velocity; _As=Asymmetry; _Var=Variability; Bold & bigger font indicates a loading >0.8; A variable in a parenthesis indicates a relevant cross-loading; A hyphen symbol in front the variable name indicates a negative factor loading; Variables with red colour indicates a relationship to the Rhythm component, black to Pace, blue to Postural Control, green to Asymmetry and purple to Variability in accordance with the variable classification in Lord et al. (2013).

The first four components were responsible for 83.66 % of the total variance. Overall, the variables loading on the Rhythm-, Variability- and Asymmetry components were clustered in a similar way as in Lord et al. (2013). The variables of the Postural Control- and Pace components, however, were more scattered in our results compared to Lord where they grouped together. The order of components is also slightly different, as Rhythm and not Pace is the first component and Variability loads ahead of Asymmetry in our study. Another difference with the study by Lord is that Step Length and Step Width load on the same component in our study, and not on two separate components (Pace and Postural Control) as in Lord et al. (2013).

3.6 Gait strategies in older and younger adults

As the younger group and the older group walked at different speeds at all speed instructions, we investigated differences in gait strategy across age at a normalized speed, namely 1.0 m/s. The PCA variable distributions of the younger and older groups walking at normalized speed are presented in Table 3-5.

Table 3-5: PCA variable distribution for the older group and the younger group at normalized walking speed (1.0 m/s).

	Normalized walking speed			
	PC1	PC2	PC3	PC4
Younger	**SL**	**ST_Var**	**StaT_As**	**-SVel**
	SW	**SVel_Var**	ST_As	SL_Var
	SS	StaT_Var	SL_As	SW_Var
	ST	SS_Var	SS_As	
	StaT		(SL_Var)	
	(SW_Var)		(SW_Var)	
% explained variance	41.54	19.96	10.87	9.40
Older	**SW**	**SW_Var**	**StaT_Var**	**SL_As**
	SL	**SL_Var**	StaT_As	(SS_As)
	ST	**SVel_Var**	ST_Var	
	StaT	ST_As	SS_As	
	SS	SS_Var		
	(StaT_As)	SVel		
% explained variance	37.31	26.36	12.02	8.07

StaT=Stance Time; SW=Step Width; SL=Step Length; ST=Step Time; SS=Single Support; SVel= Step Velocity; _As=Asymmetry; _Var=Variability; Bold & bigger font indicates a loading >0.8; A variable in a parenthesis indicates a relevant cross-loading; A hyphen symbol in front the variable name indicates a negative factor loading; Variable names in red colour indicate a relationship to the Rhythm component, black to Pace, blue to Postural Control, green to Asymmetry and purple to Variability, in accordance with the variable classification in Lord et al. (2013).

The first four components extracted accumulated 81.76% of the variance for the younger group and 83.76% for the older group. The first component for the young group and the older group are almost identical and load on variables linked with Rhythm (ST, StaT and SS), SW and SL. Variability data is grouped in the second component for the older group and split between the second and fourth component for the younger group. Asymmetry is grouped in the third component for the younger group and the older group, except ST_As which is found in the second component for the older adults. SL_As is placed in the fourth component for the older group. Pace-related variables are scattered across several components and SL and SW are clustered together in the same component for both groups.

3.7 Gait strategies in older men and women

To investigate differences in gait strategies between men and women, we ran a PCA on gait variables at normalized walking speed. See Table 3-6 for the variable distributions of men and women.

Table 3-6: PCA variable distribution for older women and older men at normalized walking speed (1.0 m/s).

	Normalized walking speed			
	PC1	PC2	PC3	PC4
Older women	**StaT_As**	**SL_Var**	**SS_Var**	**SVel**
	StaT_Var	**SL_As**	ST_Var	(SW_Var)
	-StaT	-SS		(-ST_Var)
	SS_As	SVel_Var		
	-SW	SW_Var		
	-SL			
	-ST			
	ST_As			
% explained variance	54.84	16.77	11.88	6.66
Older men	**ST**	**SW_Var**	**ST_Var**	**-StaT_As**
	SL	**SL_Var**	**StaT_Var**	SL_As
	SW	**ST_As**	(SVel)	(SVel)
	StaT	SVel_Var		
	SS	SS_Var		
	-SS_As	SVel		
% explained variance	35.90	31.65	11.57	9.21

StaT=Stance Time; SW=Step Width; SL=Step Length; ST=Step Time; SS=Single Support; SVel= Step Velocity; _As=Asymmetry; _Var=Variability; Bold & bigger font indicates a loading >0.8; A variable in a parenthesis indicates a relevant cross-loading; A hyphen symbol in front the variable name indicates a negative factor loading; Variables with red colour indicates a relationship to the Rhythm component, black to Pace, blue to Postural Control, green to Asymmetry and purple to Variability in accordance with the variable classification in Lord et al. (2013).

For older women, the first four components were responsible for 90.15% of the variance and 88.34% of the variance for the older men. Both groups load SL_As and ST_As in different components and variability data on their second component. Rhythm related variables loaded as a group on the first component for the older men, while it was split between the first two components for the (older) women. Asymmetry-variables explained more of the variance for the older women as they were clustered together in the first component for the women, while for the (older) men these variables spread on the first, second and the fourth component. Postural control variables were split for both groups but appeared more important for women as they clustered in the two first components as opposed to the first and fourth component for the men. SL and SW were coupled for both genders.

3.8 Gait strategies of older adults at different walking speeds

We also examined how gait strategies change when older adults walk slower or faster than at their preferred gait speed using PCA. The results are shown in Table 3-7.

Table 3-7: PCA variable distribution for the older group at slow and fast walking speeds.

	Slow walking speed			Fast walking speed				
	PC1	PC2	PC3	PC1	PC2	PC3	PC4	PC5
	SS_As	**StaT**	**SW_Var**	**SL**	**ST**	**ST_Var**	**SW_Var**	**SS_As**
	StaT_As	**ST**	**SL_Var**	**SW**	**SS**	**StaT_Var**	**SL_Var**	**StaT_As**
	-SW	SS_Var	**SVel_Var**	**SVel**	**StaT**	SS_Var	SVel_Var	ST_As
Older	**ST_As**	-SVel	(ST_Var)	-SL_As		(SVel_Var)		
	-SL	StaT_Var						
	-SS	ST_Var						
	SL_As	(SS)						
% explained variance	39.39	24.05	18.13	31.06	20.75	18.45	10.61	7.46

StaT=Stance Time; SW=Step Width; SL=Step Length; ST=Step Time; SS=Single Support; SVel= Step Velocity; _As=Asymmetry; _Var=Variability; Bold & bigger font indicates a loading >0.8; A variable in a parenthesis indicates a relevant cross-loading; A hyphen symbol in front the variable name indicates a negative factor loading; Variables with red colour indicates a relationship to the Rhythm component, black to Pace, blue to Postural Control, green to Asymmetry and purple to Variability in accordance with the variable classification in Lord et al. (2013).

The cumulative variance for the first three components for the older group in slow walking was 81.57% while the first five extracted components were accountable for 88.32% of the variance at fast speed. For slow walking, the older group relied more on Asymmetry data than at preferred or fast walking speeds as the Variability variables loaded on the first component for slow walking vs the last components for fast and preferred walking speeds. The Rhythm component loaded strongly on the second component for both slow and fast walking while these variables showed to be explaining most of the variance for the preferred walking where they loaded heavily on the first component. Postural control loaded on the first component for slow walking and fast walking while it was divided between the second and third components when walking at preferred speed. The Pace-related variables were scattered on to several components for all three speeds but seemed more grouped for the slow and fast speed where it loaded on the second component and the first and third components respectively. SL and SW more important at slow and fast speed.

4 Discussion

The aim of this study was to investigate the effects of age, gender, and walking speed on gait strategies by conducting PCA analyses on 16 temporal and spatial footfall parameters of gait. We found differences in gait strategies between the younger and older participants, between men and women, and between faster- and slower than normal walking speed. Each of these will be further discussed below.

4.1 Gait strategies in older adults at preferred speed

As our sample was relatively small for PCA analyses, we first compared our results with a previous study by Lord et al. (2013), using the same gait parameters. When comparing the principal components of older adults walking at preferred speed in our sample to those in Lord et al. (2013), the results are quite similar, with the components largely structured by and composed of the same variables.

For our group of older adults, the PCA yielded four components for walking at preferred speed, compared to five components in the study by Lord et al. (2013). Temporal variables (Rhythm), spatial variability variables (Variability), and asymmetry in temporal variables (Asymmetry) were separated onto different components in both studies. This is indicative that each component, characterized by highly related gait variables, is unique and independent from other components.

Temporal variability variables (Pace) were spread across two components in our study (clustered with Rhythm and Asymmetry) and not on a separate Pace domain as in Lord et al. (2013). This result could be supported by the statistical relationship between variables, and the related underlying mechanism between these variables (Step Time and its variability, Single Support and its variability, and the variability and asymmetry of Stance Time). It is also possible that our small sample size compared with Lord`s can partly explain these diverging results.

The Postural Control component in Lord consisted of Step Length asymmetry and Step Width, whereas Step Width loaded with Step Length and Step Velocity in our study, representing spatial variables. This combination of variable clustering in our study resembles the Postural Control component in Thingstad et al. (2015), where Step Length and Step Width in addition to walk ratio (SL/Cadence) formed the Postural Control component. Step Length and Step Velocity are highly correlated by default, as Step Velocity is calculated by dividing Step Length by Step Time. Step Width and Step Length are both spatial variables that regulate the base of support in the medio-lateral and anterior-posterior directions, respectively. Thingstad and colleagues (2015) argued that this clustering of variables represented cautious gait commonly seen in older age, characterized by reduced Step Length, together with increased Cadence and Step Width. This could be an attempt to control lateral excursions of the upper body, thereby obtaining increased stability during gait without reducing gait speed.

Compared to Lord et al. (2013), Rhythm was more important than Pace for our group of participants, indicating a decline in Pace. Also, Variability was more important than Asymmetry, indicating an increase in Variability. These findings were supported by Lord who suggested that Rhythm and Asymmetry were less susceptible to age and more robust compared with Variability, Pace and Postural Control (Lord et al., 2013). Stance Time, Step Time and Single Support time (Rhythm) are usually stable parameters at normal speed, and they are understood to be controlled by the automatic stepping mechanism of gait. Therefore, variability in these parameters can be interpreted as an abruption of the automatic stepping mechanism (Brach et al. 2008), while increased Step Width variability probably reflects a strategy to cope with instability (Gabell & Nayak, 1984), suggesting different underlying constructs for different variability measures (Moe-Nilssen et al., 2010). As argued by Lord et al. (2013), this might be a possible explanation for the separate loading of the spatial variability variables seen in their study as well as in our study. Verlinden and colleagues (2013) also found that Pace, Variability and Base of Support decline with age, but not Rhythm, with an especially early onset of decline for Variability which is seen already from 55-60 years. The older participants in our group were significantly older than the subjects in Lord et al. (2013), although both groups were above the age range of early decline onset as described by Verlinden et al. (2013). Nevertheless, the assumptions regarding Variability and age are not consistent. For example, Hollman and colleagues (2011) also found that Pace was linked with age, but not Variability. It should be noted, however, that the latter study had a smaller sample size and compared older adults above 70 years, beyond the age range of early decline onset. Moreover, the Variability component in Lord et al. (2013) only consisted of spatial variability variables, while the Variability components of Hollman et al. (2011) and Verlinden et al. (2013) contained a combination of spatial and temporal variability parameters (variability in Rhythm). The latter was linked with Pace in Lord et al.`s study (2013) and might possibly explain the different results between the studies. The separate loading of spatial variability variables in our study is supported by several other studies who have argued that variability might not be a singular construct (e.g., Moe-Nilssen et al., 2010), and that different gait variability parameters are explained by different mechanisms.

Differences in component arrangements and in variable clustering between the current study and earlier studies might partly be explained by differences in the populations studied as well. While Lord et al.`s (2013) group of older participants were healthy with a mean age of just under 70 years, the participants of Thingstad et al. (2015) had experienced a hip fracture and were on average over 80 years. Our group of elderly were closer to the latter in age, but closer to Lord et al.`s (2013) population regarding MMSE scores and health profiles.

4.2 Effects of age

Surprisingly, at normalized speed, the first PCA components for the younger and older groups are almost identical! To our knowledge, a comparison between younger and older participants at normalized speed has not been conducted previously. These results are interesting, as they suggest that the most important sources of variance can be the same for both age groups. Both groups loaded the spatial variables Step Length and Step Width, and temporal variables (Rhythm) in their first component, which supports the findings of Verlinden et al. (2013) and Lord et al. (2013) that the importance of Rhythm as such does not seem to decline with age.

The second component consisted of a combination of temporal and spatial variability variables for both groups, but while spatial variability (Variability) was more important for the older group, temporal variability (Pace) explained more of the variance for the younger group. This is line with previous work, indicating that pace or gait velocity declines with age (Blanke & Hageman, 1989; Bohannon, 1997). Kang and Dingwell (2008) argued that the larger Step Length variability seen in a range of gait speeds for older adults compared to younger people was not related to their slower speed as such, but rather to reduced muscular strength and flexibility in the older group. Menz and colleagues (2003) found that maximum gait speed is positively associated with quadriceps and ankle dorsiflexion strength. Sadeghi et al. (2002) reported that in older people, knee flexor and extensor muscles mainly provided balance control, while in younger people, these muscles also aided propulsion and longer step lengths, contributing to increased gait speed.

While the age-related decline also affects body composition, where a gradual increase in body fat percentage and the reduction in muscle cross-sectional area are the main influencers (Larsson & Ramamurthy, 2000), walking in older age may become even more difficult. Especially as the upper body accounts for up to two thirds of the body mass (Winter, 1995), further complicating the task of controlling body sway, possibly resulting in adaptation strategies resembling cautious/older gait. The older group in our study, women in particular, had higher BMI scores than the younger group, which possibly contributed to differences in walking strategies.

The division of the variability variables into Variability and Pace seen in Lord et al.`s (2013) study and to a lesser degree in our own study, was rather surprising to the authors as they predicted that these variables would load together on the Variability component, in agreement with previous studies. However, this may further illustrate that variability is a complex concept that may have several underlying structures.

The third component contained temporal asymmetry variables (Asymmetry) and spatial asymmetry variables (Postural Control) for the younger group, while in the older group temporal asymmetry (Asymmetry) and temporal variables (Pace) loaded to the third component. The younger and older groups were similar with regards to Asymmetry, which is perhaps not surprising as our group of older adults were relatively healthy without known pathology. This is also in line with the findings of Lord and colleagues (2013), who reported that the importance of Asymmetry was less age-sensitive than the other components, suggesting that Asymmetry could be more evident when gait pathology is involved (Lord et al., 2013).

4.3 Gait strategies in older women and men

The current study indicated that the gait of older women and older men is described by different components and constituent variables. For older women, the first PCA component consisted of temporal variables, including temporal asymmetry (Asymmetry) and temporal variability, in addition to the spatial variables Step Width and Step Length. The first PCA component for the older men consisted of temporal variables (Rhythm), in addition to the spatial variables step length and step width as well as single support asymmetry.

These findings indicate that Asymmetry explained more of the variance in the first component for the older women compared to men, suggesting that Asymmetry was more important for gait in the older women while Rhythm explained more of the variance for older men. Another interesting difference between the genders was the aligning of Stance Time and its variability and asymmetry variables as the primary constituting variables for the first component for the older women. This finding suggests that Stance Time plays a more prominent role in describing older female gait and is less important for the men. Older women spent less time in Stance than the older men, perhaps to compensate for smaller Step Lengths.

In addition, women walked with narrower steps, but increased Step Width variability compared to men. This is consistent with earlier findings of Hollman et al. (2011) who linked height to lower Rhythm, Variability and Base of Support, but increased Pace. Furthermore, they found that women had lower Pace and Base of Support, but higher Rhythm compared to men (Hollman et al., 2011). The older men in our study scored significantly higher than the older women on the Physical functioning (SF-36), indicating a better physical functioning for the men which likely explains some of the differences between the genders. When corrected for gait speed, constituting variables of the Rhythm component in our study were all almost identical to the normative data presented by Hollman et al. (2010).

The larger importance of Asymmetry for the older women compared to men is supported by an earlier unpublished PCA study (Vereijken et al., 2015) who found Asymmetry to explain more of the variance for older women walking at preferred speed than for older men. Other studies have shown that age-related increases in Swing Time asymmetry (e.g., Yogev et al., 2007) are associated with higher risk of falling. As gait asymmetry negatively influences the rhythmicity of walking, an increase in asymmetry could increase fall risk. Larger variability and asymmetry levels have been observed in the gait of older women with interlimb strength imbalances (e.g., Laroche et al., 2012). Unfortunately, the lower leg strength tests for the older group performed prior to gait trials were assessed bilaterally in the current study, so any possible differences in left and right leg strength could not be investigated. Future studies assessing variability and asymmetry characteristics in gait should investigate and consider possible interlimb strength differences.

4.4 Gait strategies of older adults when walking at different speeds

Our results indicated that gait speed affects gait components both in number, importance regarding explained variance, and associated variables.

Only three components were extracted for slow speed, while five components were obtained for fast speed. This indicates that at slow speed, a larger number of variables are correlated and thereby provide less unique information about the data set compared to gait at fast speed, which yielded additional independent components. At slow speed, temporal asymmetry data (Asymmetry) clustered with spatial variables and spatial asymmetry data (Postural Control) as well as temporal variable single support in the first component, while temporal variables (Rhythm) loaded with temporal variability data (Pace) to the second component. Spatial variability data (Variability) loaded separately in the third component.

While the gait parameters at slow speed were combined in fewer components, the structure of the PCA at fast speed were more like Lord et al.`s (2013), where temporal variables (Rhythm), temporal variability variables (Pace), spatial variability variables (Variability) and temporal asymmetry variables (Asymmetry) loaded on separate components. The first component consisted of spatial variables and Step Length asymmetry (Pace and Postural Control) and stand out as different compared to our PCA results from walking at preferred speed. Temporal asymmetry (Asymmetry) appeared to be highly relevant for gait at slow speed, but the least important component for gait at fast speed. At preferred speed, Asymmetry was also the least important compared to the other components, so it is interesting that Asymmetry is important for gait at slow speed. Gait symmetry is often assumed in the gait literature, and asymmetry has often been considered as a sign of pathology (Sadeghi et al, 2000). Several studies, however, have reported some level of step asymmetry in healthy subjects as well. Sadeghi and colleagues (1997), for instance, found functional asymmetry in their study of muscle power and mechanical energy during gait in able-bodied men. Functional asymmetry is related to the degree of involvement of the right and left legs to control and propel human gait, where one leg is often more dominant for controlling and stabilizing the body during walking, while the other has a stronger influence on mobilizing the body through propulsion (e.g., Kozlowska et al., 2017). The higher importance of asymmetry at slow speed might reflect this functional limb difference, where the stabilizing limb spends more time in contact with the ground than the mobilizing limb.

The importance of Step Width, Step Length and their asymmetry was more pronounced for fast and slow speeds than for preferred speed. For Step Width, this might reflect the curvilinear relationship (u-shaped) with gait speed, with the lowest Step Width at preferred speed and higher Step Widths at slower and faster speeds (Helbostad & Moe-Nilssen, 2003). For the older group in our study, Step Width increased with gait speed in a linear manner, as previously reported by Sekiya et al. (1997) as well. Thus, the results are inconclusive regarding Step Width. Any estimate, however, is restricted by the accuracy of the measuring equipment, and while reliability of the measurements provided by the GaitRite are generally high, this is not the case for Step Width. The sensors in the mat are placed 1.27 cm apart from each other, and when one or two sensors fail to register a footprint, this could result in large differences between steps and trials (cf. Menz et al., 2004), impairing step width outcomes in particular. Step Length increases with gait speed and the power exerted by the calf-muscles during push-off (MacLellan & Patla, 2006). Step Length asymmetry may be caused by compensational adjustments after a wider step to the side, or simply be due to speed variations from step to step, while other potential contributing factors to asymmetry in Step Length are laterality, asymmetry in strength or flexibility between the legs, pathology, or inter-limb leg length differences (Sadeghi et al., 2000). When Stance Time increases in one leg, the contralateral leg compensates and moves with an increased swing time.

Rhythm was more important than Step Length and Step Width at preferred speed, which is in line with a previous study by Kito and Yoneda (2006), who found that walking rhythm (cycle duration) was the most stable and most dominant parameter in casual walking of healthy young men compared to stride length and walking speed, with the latter being the least stable parameter. They argued that their findings imply that walking rhythm plays an important executive and controlling role of casual walking, potentially related to optimizing walk economy (Kito & Yoneda, 2006). However, Rhythm and Variability were less important for slow and fast speeds compared to preferred speed for our older group, indicating that casual gait potentially is more harmonic and stable, and cost effective with regards to energy expenditure than walking at slower and faster speeds.

Interestingly, for fast speed, the older adults relied on spatial and temporal parameters that reflect Pace. At preferred speed, Rhythm was important, and the older adults seemed to rely more on intralimb control (Variability), while at slow speed postural control using an interlimb approach (Asymmetry) where the left and right legs take different actions during walking was more pronounced.

While several studies have shown that moderate Step Width variability is required for proper foot position adjustment and maintaining balance control during gait, both higher and lower Step Width variability at preferred speed has been associated with falls (Brach et al., 2005). It is important, however, to acknowledge that even though both variability and asymmetry have been connected to falls and abnormal gait patterns, the concepts in themselves are not necessarily negative. Corrective steps to avoid obstacles or to regain or maintain balance control, the slowing or acceleration of gait speed or even walking in a non-straight line or on uneven surfaces will naturally be captured as gait variability or asymmetry but may rather portrait flexible and adaptable locomotion.

Reliable measures for velocity and cadence can be acquired from 10-20 strides, although spatiotemporal stride variability measures may necessitate data collected from twenty (Lindemann et al., 2008) to sixty strides to become reliable (Hollman et al., 2010). Unfortunately, an adequate number of steps was not obtained during the data collection in our study and should be considered when interpreting these variability and asymmetry characteristics. Insufficient data might also be a contributing factor to the diverging results regarding gait variability found in the literature. Future studies targeted to investigate effects of speed on variability and asymmetry characteristics of gait should include a range of gait speeds and a sufficient step quantity to avoid potential statistically spurious results. Thus, future studies that investigate effects of speed in gait should include a range of gait speeds and ensure sufficient steps per trial to be able to calculate reliable variability and asymmetry data.

4.5 Methodological considerations, strengths and limitations

Several participants from the younger group, in particular the women, walked faster than our chosen normalized velocity of 1.0 m/s. To avoid predicting data points far outside the value range of the data, we decided to use the closest data point to 1.0 m/s. This was done for 50% of the younger women and 20% of the younger men, as their slow speeds exceeded the normalized speed. Hence, their normalized gait speed ended up slightly higher than for the other participants. Gait speed is commonly a result of step length and cadence (step frequency) (Callisaya, 2008), but several gait variables change as gait speed changes. By obtaining the closest value, mean step velocity and all variability and asymmetry variables were affected, as their data points originated at the speed closest attainable to 1.0 m/s, and thus deviating from the normalized data. Hence, some caution should be taken when comparing these gait variables.

The strengths of this study are the inclusion of many gait variables, three different gait speed instructions, equal recruitment of both genders, and the comparison with a control group of healthy young adults on a common, normalized gait speed. However, there are some limitations to our study as well, most importantly a relatively small sample size. We enrolled 40 participants in our study, which is a rather small sample size for principal component analysis. Further, we conducted PCAs on different subgroups of the sample, further reducing sample size to 10-20 participants in each subgroup. With larger sample sizes, the results would be more reliable. However, compared to larger studies like Lord et al. (2013) and Thingstad et al. (2015), our results for the older group walking at preferred speed were quite similar. Thus, we argue that the results of our study are relevant and interesting, especially for comparisons at normalized speed as this had not been done before. Furthermore, reliability of the variability and asymmetry calculations increases with a larger number of steps. Unfortunately, for some participants that walked with long step lengths, an inadequate number of steps per trial was available to calculate solid variability and asymmetry variables in this study, especially for the younger adults walking at fast speed. With enough step data gathered through additional gait trials and speed instructions, a normalizing procedure with curvilinear interpolation, would be achievable for all data (without "closest fit" results), which subsequently would make the current gait data more reliable. Finally, our sample consisted of healthy younger and older adults only, restricting generalizability to similar populations only. Nevertheless, the current study and its results can stimulate similar research on other populations and perhaps even use the current results for comparison.

5 Conclusion

Gait strategies are affected by age, gender and walking speed. Comparing older and younger adults walking at the same, normalized speed indicated that Pace changes with advancing age, but not Rhythm. Furthermore, older women relied more on Asymmetry and less on Rhythm than older men, with Stance Time in particular characterizing female gait. Finally, in older adults, Pace seems more important for fast speed, with Asymmetry playing a minor role when walking fast. Rhythm was the most influential component at preferred speed, indicating harmonized, energy optimized gait when speed was self-selected. At preferred and fast speeds, older adults seem to focus mostly on intralimb control (Variability). In contrast, at slow gait speed an interlimb strategy was dominant, in which the actions of the left leg differed from the right leg (Asymmetry).

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