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Outcome-dependent effects of walking speed and age on quantitative and qualitative gait measures

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ABSTRACT

Background: Walking speed predicts many clinical outcomes in old age. However, a comprehensive assessment of how walking speed affects accelerometer based quantitative and qualitive gait measures in younger and older adults is lacking.

Research question: What is the relationship between walking speed and quantitative and qualitive gait outcomes in younger and older adults?

Methods: Younger (n = 27, age: 21.6) and older participants (n = 27, age: 69.5) completed 340 steps on a treadmill at speeds of 0.70 to a maximum of 1.75 m·s-1. We used generalized additive mixed models to determine the relationship between walking speed and quantitative (stride length, stride time, stride frequency and their variability) and qualitive (stride regularity, stability, smoothness, symmetry, synchronization, predictability) gait measures extracted from trunk accelerations.

Results: The type of relationship between walking speed and the majority of gait measures (quantitative and qualitative) was characterized as logarithmic, with more prominent speed-effects at speeds below 1.20 m·s^{-1}. Changes in quantitative measures included shorter strides, longer stride times, and a lower stride frequency, with more variability at lower speeds independent of age. For qualitative measures, we found a decrease in gait symmetry, stability and regularity in all directions with decreasing speeds, a decrease in gait predictability (Vertical, V, anterior-posterior, AP) and stronger gait synchronization (AP-mediolateral, ML, AP-V), and direction dependent effects of gait smoothness, which decreased in V direction, but increased in AP and ML directions with decreasing speeds. We found outcome-dependent effects of age on the quantitative and qualitative gait measures, with either no differences between age-groups, age-related differences that existed regardless of speed, and age-related differences in the type of relationship with walking speed.

Significance: The relationship between walking speed and quantitative and qualitative gait measures, and the effects of age on this relationship, depends on the type of gait measure studied.

1. Introduction

Human gait changes quantitatively and qualitatively during healthy aging. Changes in gait quality with aging [1] are assessed by regularity [2], predictability [3], local stability [4], symmetry [5] and smoothness [6] measures of trunk accelerations [1,7]. Quantitative changes include a decline in preferred walking speed (PWS) by 16% per decade [8] involving correlated modifications in spatiotemporal characteristics. Although speed is an intrinsic determinant of gait performance [9], a comprehensive assessment of the effects of age and walking speed on quantitative and qualitive gait measures is lacking. Such analyses would provide insights into whether the quantitative and qualitative changes

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with aging are the result of differences in walking speed or an inherent property of the aging neuromuscular system.

The effects of walking speed on gait measures are outcome-dependent in younger adults. Cadence increases linearly with speed, whereas increases in step lengths stabilize at higher speeds [10], meaning that step lengths are more constrained by physical aspects than cadence. Because metabolic cost [11], muscle activity [11] and stability [12] tend to be optimized at PWS, one would expect that gait quality would be optimal around PWS. However, such data are inconclusive, as for gait symmetry, quantified using harmonic ratio (HR), and the magnitude of variability of spatiotemporal gait measures, usually expressed by the coefficient of variation (CV) or standard deviation (SD), both U-shaped (optimum around PWS) [13–15] as well as linear [16–18] relationships with walking speed have been reported in younger adults aged ~25 y. Additionally, speed-effects on local dynamic stability in anterior-posterior (AP), vertical (V) and mediolateral (ML) direction, quantified by the Maximum Lyapunov Exponent (λ_{max}) have been characterized as negative linear (120–80% PWS) [14,19], positive linear (0.62–1.72 $m \cdot s^{-1}$) [20], and quadratic (0.62–1.72 $m \cdot s^{-1}$) [20].

One source of inconsistency that could underlie the variation in the nature of the relationship between gait quality and walking speed, is that speed-comparisons were done at absolute speeds, speeds relative to PWS, or at self-selected speeds. Testing at an absolute speed ignores a person's PWS and sensitivity to walking speed [21], whereas absolute speed differences occur when testing at self-selected speeds. Therefore, testing at both absolute and relative speeds, could help to get a better understanding of the effects of age and gait speed on gait quality and quantity.

Studies that compared speed-effects between younger and older adults, reported that both groups' gait is more variable and stable at lower speeds (120–80%PWS), but older compared with younger adults are more variable and unstable at the same speeds [18,19,22]. Gait symmetry increased with overground walking independent of age, but in old older adults (82.5 ± 2.2) HRs in AP direction decreased with speed [16]. Other gait quality measures, amongst which gait smoothness and regularity, tended to increase with speed (treadmill, 0.63–1.72 $m \cdot s^{-1}$) in older adults [23], but such data are lacking in younger adults.

The aim of the current exploratory study was to determine the effects of walking speed on quantitative and qualitative gait measures in younger and older adults. Specifically, we examined if age and the type of walking speed (absolute, PWS) would affect the relationship (linear, non-linear) between walking speed and measures of gait quality and quantity. Based on the extant data, our general hypothesis was that both quantitative and qualitative gait measures would be sensitive to walking speed and age so that the type of relationship with walking speed would vary with measure and age.

2. Methods

2.1. Participants

Healthy young ($n = 27$, 14F) and older adults ($n = 27$, 14F) volunteered in the study (Table 2). Inclusion criteria were age 18–30 and 60–90 and either gender. Participants were acquaintances of the researchers or recruited by word of mouth or through printed advertisements on notice boards at various sites in the community. Exclusion criteria for all participants were: neurological or orthopaedic conditions, inability to walk for five minutes without a walking aid, a fall in the past year, or a hip or knee replacement during the past three years. The study was approved by the Local Ethical Committee and conducted in accordance with the declaration of Helsinki. All participants gave written informed consent prior to participation in the study.

2.2. Procedure

To get an indication of the general health and functioning of our participants, we assessed functional capacity using the 2-Minute Walk Test (2MWT) [24], quantified maximal grip strength of the dominant hand using a Jamar hand-held dynamometer (average of three trials), and examined cognitive functioning using the Montreal Cognitive Assessment (MoCA) [25]. To determine overground PWS, participants walked for three minutes in an indoor hallway. The time used to traverse 10 m straight tracks along the path was averaged to determine PWS. Additionally, we determined PWS on an instrumented split-belt treadmill (M-Gait, Motekforce Link, Amsterdam, The Netherlands) by slowly increasing and decreasing treadmill speeds. After walking three minutes at PWS, participants walked at speeds from 0.70 to 1.75 $m \cdot s^{-1}$ with increments of 0.15 $m \cdot s^{-1}$. During all treadmill conditions, participants wore a safety harness around their upper trunk, which did not constrain walking. Furthermore, participants were instructed to walk as naturally as possible in the middle of the belt and touch the handrails only when the treadmill was speeding up/slowing down.

After walking 340 steps at a speed, participants rated their perceived fatigue on a visual analog scale (0 = not fatigued, 10 = exhausted). The next speed started after seated rest for 1–2 min. When participants indicated that the treadmill speed was too high, testing stopped.

2.3. Gait measures

During gait, AP, ML, and V trunk accelerations were recorded at 100 Hz by a built-in accelerometer of an Iphone SE (iOS 12, Apple Inc.), fixed with a belt near the level of lumbar segment L3 [26]. Acceleration signals were analysed off-line using MATLAB (version 2020a, the Mathworks Inc.). After detrending, signals were corrected for horizontal tilt, and except for the calculation of gait stability and predictability, low-pass filtered (Butterworth filter, 2nd order, cut-off frequency 20 Hz). Twenty steps were removed at the beginning and end of the signal, leaving 300 steps of steady-state data for analysis.

The following gait measures were computed from the acceleration signals (see Appendix for detailed description): Stride length (Mean, SD), Stride time (Mean, SD), Stride frequency, Gait regularity (V, AP), Stride frequency variability (V, ML, AP), Gait smoothness (V, ML, AP), Gait symmetry (V, ML, AP), Gait stability per stride (V, ML, AP), Gait predictability (V, ML, AP), Gait synchronization (V-ML, ML-AP, AP-V).

2.4. Generalized additive modelling

Using the *mgcsv package (version 1.8–34;* [35]) in R software (R version 3.6.1, R core team, 2019), generalized additive mixed models (GAMMs) were used to model the effects of age and speed on gait measures [27]. So-called smooth functions were constructed using a thin plate regression spline, which models (non)linear patterns by using a combination of increasingly complex basis functions [28] (e.g., linear logarithmic, quadratic, etc.) and were fitted with the maximum likelihood (ML) estimation method. Table 1 shows an overview of the GAMM models defined.

To select the model that best fit the data, models 1–3, were compared using the Akaike Information Criteria (AIC). An AIC score of at least 2 AIC units lower indicates an improved model with a more accurate (relative) goodness-of-fit [27]. To examine the effects of individual variability on speed-and age effects, random intercepts (RI) and factor smooths (FS) were added to the final model (last two rows Table 3). Since AIC scores cannot be used for models varying in their random effects [29], a Chi^2-test on the model (ML) scores was used, to determine whether RI and FS improved the final model.

In addition to effects on absolute walking speeds, GAMM analyses were performed on relative speeds, where the absolute treadmill speeds were expressed as a percentage of preferred treadmill and overground walking speed. For all analyses, statistical significance was set at $p < 0.05$.

Table 1
Overview and description of the generalized additive mixed models used in the study.

Model	Type of effect examined	Formula	Explanation
Model 1	Speed effect	$k_4(Y_j) = f_1(X_j) + \alpha$	Model 1 determines the presence of a general speed effect, where Y is the gait measure, X_j are the treadmill speed with 7 levels varying from 0.70 to 1.75 m·s^{-1}, α is the intercept. The k-parameter, which restricts the number of basis functions used to construct the smooth and should be set at most half the number of unique data points [34], was set to 4.
Model 2	General age effect across speeds	$k_4(Y_{i,j,l}) = f_1(X_j) + \beta_1 X_l + \alpha$	In model 2, a linear contrast, $\beta_1 X_l$, between groups is added, where X_l is a factor that contains the group levels young or old, and β_1 a regression coefficient. A significant contrast indicates that on average across speeds younger and older adults differ from each other.
Model 3	Different speed smooths for age groups	$k_4(Y_{i,j,l}) = f_1(X_j)X_l + \beta_1 X_l + \alpha$	In model 3, $f_1(X_j)X_l$, indicates a separate smooth for both age groups, which could indicate a different type of speed-effect in both groups. To model a constant difference between groups as smooths are centered around zero, the linear group-contrast is also included in this model.
Final Model a	Model 1,2,3 with the addition of random intercepts (RI)	*Final model* $+ \alpha_{ij}$	To either model 1,2, or 3, which is determined after model comparison, RI are added to examine the effect of individual variability on speed-and age effects. RI allow varying intercepts per individual. i are participants 1–55.
Final Model b	Model 1,2,3 with the addition of factor smooths (FS)	*Final model* $+ f_2(X_{ij})$	To either model 1,2, or 3, which is determined after model comparison, FS are added to examine the effect of individual variability on speed-and age effects. FS allow the general smooth to vary non linearly per individual [27]. The degree of smoothness is controlled to the first derivative.

3. Results

Table 2 shows participants characteristics. One older participant was excluded for being unable to walk at PWS per protocol. All younger adults reached 1.75 m·s^{-1}. The highest walking speed attained in the older adults was 1.15 m·s^{-1}($n = 1$), 1.45 m·s^{-1}($n = 3$), and 1.60 m/m·s^{-1}($n = 1$) and 1.75 m·s^{-1}($n = 22$).

3.1. Speed and age effects

Table 3 shows the GAMM results and Figs. 1–2 visualize the speed effects in the two age groups based on the final models described below.

A speed effect (*Model 1,* $p < 0.0001$) was present in all gait measures. The linear age contrast *(Model 2)* improved the model for all gait measures *($p < 0.05$, >2 AIC units lower*), except for stride time variability, gait stability (V), stride regularity (V) and gait synchronization (AP-ML). Model comparison revealed that the best fit was achieved with *Model 2* for stride length, stride length variability, stride frequency variability (V, ML, AP), stride regularity (AP), gait smoothness (AP), gait symmetry (V,ML,AP), gait synchronization (AP-ML) and gait predictability (AP). Across speeds, older vs. younger adults were less regular (AP: 9.4%), made longer steps (2.7%), had more variable step lengths (7.7%) and stride frequency across all directions (V: 6.6%, ML: 9.0%, AP: 15.7%), were less smooth in AP direction (6.8%), less predictable in AP direction (3.9%), and AP and ML accelerations were more synchronized (6.6%). Effects of HRs were speed dependent; as for V and AP directions, older vs. younger adults were less symmetrical (V: 9.8%, AP: 21.5%) across all speeds, whereas in ML direction older vs. younger adults were slightly more symmetrical across all speeds (5.4%).

Table 2
Participants' characteristics.

Variable	Young (N = 27)		Old (N = 27)	
Age (years)[a]	21.56	(2.12)	69.48	(4.85)
Age range (years)	19- 26		60- 86	
Gender (male/female)	13/ 14		13 /14	
Height (cm)[a]	178.96	(10.58)	171.89	(8.30)
Leg length (cm)	87.19	(6.73)	84.13	(4.69)
Mass (kg)	70.22	(11.44)	71.52	(12.64)
BMI	19.56	(2.57)	20.74	(3.1)
PWS Treadmill (m·s^{-1})[a]	1.23	(0.11)	1.16	(0.16)
PWS Overground (m·s^{-1})	1.55	(0.14)	1.55	(0.21)
2MWT (m)[a]	207.35	(20.16)	175.51	(24.69)
Handgrip strength[a]	78.92	(6.94)	68.70	(9.46)
MoCA[a]	28.19	(1.49)	27.08	(1.74)
Fatigue				
0.70 m·s^{-1}	0.98	(0.91)	1.34	(1.24)
0.85 m·s^{-1}	1.00	(0.79)	1.50	(1.46)
1.00 m·s^{-1}	1.17	(0.89)	1.62	(1.67)
1.15 m·s^{-1}	1.28	(0.87)	1.74	(1.80)
1.30 m·s^{-1}	1.56	(0.89)	1.78	(1.48)
1.45 m·s^{-1}	1.84	(1.07)	2.00	(1.52)
1.60 m·s^{-1}	2.29	(1.33)	2.24	(1.54)
1.75 m·s^{-1}	2.89	(1.50)	2.80	(1.76)

Data are expressed as mean (± SD), PWS = Preferred walking speed, 2MWT = 2-Minute Walk Test, MoCA = Montreal Cognitive Assessment [a]$p < 0.05$

A different smooth for younger and older adults (*Model 3)* revealed the best fit for stride time, stride frequency, gait smoothness (V, ML), gait stability (ML, AP), gait synchronization (AP-V) and gait predictability (V, ML)(> 2 AIC units lower). For these measures, the differences in the type of smooth for younger and older adults can be seen in Table 3 (Model 3, columns Edf$_{\mathrm{Young}}$, Edf$_{\mathrm{Old}}$). For these measures, older adults had shorter stride times (6.3%) and higher stride frequency (6.8%) across speeds. Older vs. younger adults were smoother in V and ML directions at speeds below ~1.70 m·s^{-1} (V: 15.3%, ML: 92.6%), more stable (24.7%) at speeds below ~1.47 m·s^{-1} in ML direction, less stable (17.0%) at speeds below ~1.47 m·s^{-1} in AP direction, more predictable (7.0%) in ML direction at speeds between 0.70 and 1.30 m·s^{-1}, and more predictable (11.6%) at speeds faster than ~0.77 m·s^{-1} in V direction. At speeds faster than ~1.00 m·s^{-1}, acceleration patterns in AP and V directions were more synchronized (7.5%) in older compared to younger adults.

The final models improved ($p < 0.0001$) and explained variance increased by adding random intercepts (*Final model a*, R^2 spatiotemporal: >94%, R^2 gait variability: 61%−77%, R^2 gait quality: 61%−88%) and factor smooths (*Final model b*, R^2 spatiotemporal: 99%, R^2 gait variability: 80%−90%, R^2 gait quality: 86%−98%, see Table 3, last two columns).

3.2. Effects of relative speeds

The final model differed for 9 out of 25 gait measures at absolute vs. relative speeds. For six measures, differences concerned a (non)-significant age intercept (Model 1 vs Model 2, Table 4). For stride length, also differences in the type of curve, as indicated by the estimated degrees of freedom, were found. Additionally, for gait predictability (V), gait stability (AP) and gait smoothness (ML), differences were observed in whether or not the best fit was achieved with a different smooth for younger vs older adults (Model 2 vs Model 3, Table 4). The Appendix details the GAMM results for relative speeds.

Table 3
Generalized additive mixed models results for absolute walking speeds.

	Model 1				Model 2				Model 3						Final Model	
Variable	pValue	Edf	AIC	r^2	pValue	Edf	AIC	r^2	pValue young	pValue old	Edf young	Edf old	AIC	r^2	RI	FS
Model 1																
Gait synchronization (ML-V)	**0.0123**	**2.24**	**-757.90**	**0.03**	0.7178	2.24	-756.02	0.02	0.0538	0.0032	1.99	1.00	-758.64	0.03	0.71	0.95
Gait stability (V)	**<0.0001**	**2.88**	**442.39**	**0.71**	0.1028	2.88	441.68	0.71	<0.0001	<0.0001	2.79	2.76	441.26	0.71	0.86	0.97
Stride regularity (V)	**<0.0001**	**2.91**	**-917.36**	**0.69**	0.0630	2.91	-918.87	0.69	<0.0001	<0.0001	2.84	2.80	-914.90	0.69	0.84	0.93
Stride time variability	**<0.0001**	**2.93**	**-3041.89**	**0.64**	0.7483	2.93	-3040.00	0.64	<0.0001	<0.0001	2.87	2.85	-3039.62	0.65	0.77	0.90
Model 2																
Stride length	<0.0001	1.00	-606.37	0.77	**0.0039**	**1.00**	**-612.79**	**0.77**	<0.0001	<0.0001	1.00	1.00	-613.34	0.77	0.96	0.99
Stride length variability	<0.0001	2.52	-2938.88	0.21	**0.0049**	**2.53**	**-2944.95**	**0.23**	<0.0001	<0.0001	2.46	1.92	-2941.66	0.23	0.61	0.80
Frequency variability (V)	<0.0001	2.85	-1692.79	0.57	**0.0346**	**2.86**	**-1695.33**	**0.57**	<0.0001	<0.0001	2.69	2.75	-1690.45	0.57	0.74	0.81
Frequency variability (ML)	<0.0001	2.60	-1649.02	0.52	**0.0007**	**2.62**	**-1658.59**	**0.53**	<0.0001	<0.0001	2.26	2.50	-1657.39	0.53	0.69	0.80
Frequency variability (AP)	<0.0001	2.87	-1549.23	0.57	**<0.0001**	**2.88**	**-1568.84**	**0.59**	<0.0001	<0.0001	2.75	2.78	-1563.52	0.58	0.75	0.85
Stride regularity (AP)	<0.0001	2.42	-731.48	0.19	**<0.0001**	**2.50**	**-785.96**	**0.29**	<0.0001	<0.0001	2.17	2.21	-783.66	0.30	0.80	0.88
Gait symmetry (V)	<0.0001	1.62	1255.02	0.43	**<0.0001**	**1.73**	**1234.53**	**0.46**	<0.0001	<0.0001	1.80	1.00	1235.96	0.46	0.78	0.91
Gait symmetry (AP)	<0.0001	1.00	1233.80	0.25	**<0.0001**	**1.00**	**1160.52**	**0.38**	<0.0001	<0.0001	1.00	1.00	1162.47	0.37	0.75	0.91
Gait symmetry (ML)	<0.0001	1.00	929.18	0.09	**0.0260**	**1.00**	**926.18**	**0.10**	<0.0001	0.0003	1.00	1.00	926.39	0.10	0.61	0.86
Gait smoothness (AP)	<0.0001	2.31	-632.21	0.59	**0.0002**	**2.34**	**-644.41**	**0.60**	<0.0001	<0.0001	2.05	1.82	-640.51	0.60	0.85	0.97
Gait predictability (AP)	<0.0001	2.37	-371.45	0.39	**0.0109**	**2.38**	**-376.06**	**0.40**	<0.0001	<0.0001	2.09	1.97	-371.04	0.39	0.80	0.95
Gait synchronization (AP-ML)	<0.0001	2.61	-749.23	0.14	**<0.0001**	**2.64**	**-768.18**	**0.18**	<0.0001	<0.0001	2.46	2.27	-763.07	0.18	0.59	0.93
Model 3																
Stride time	<0.0001	2.79	-790.18	0.68	<0.0001	2.82	-875.39	0.74	**<0.0001**	**<0.0001**	**2.75**	**2.53**	**-900.33**	**0.76**	0.94	0.99
Stride frequency	<0.0001	2.37	-1069.31	0.69	<0.0001	2.46	-1157.44	0.75	**<0.0001**	**<0.0001**	**2.20**	**1.43**	**-1162.12**	**0.76**	0.96	0.99
Gait stability (ML)	<0.0001	1.00	1137.01	0.16	<0.0001	1.00	1095.66	0.24	**<0.0001**	**0.0020**	**1.00**	**1.00**	**1070.54**	**0.29**	0.76	0.95
Gait stability (AP)	<0.0001	1.27	797.20	0.07	<0.0001	1.49	776.33	0.12	**0.0157**	**<0.0001**	**1.00**	**1.00**	**773.96**	**0.12**	0.76	0.90
Gait smoothness (V)	<0.0001	2.66	-548.66	0.52	<0.0001	2.68	-602.05	0.58	**<0.0001**	**<0.0001**	**2.52**	**2.44**	**-609.07**	**0.59**	0.85	0.98
Gait smoothness (ML)	<0.0001	2.59	-226.63	0.61	<0.0001	2.66	-310.00	0.68	**<0.0001**	**<0.0001**	**2.50**	**2.37**	**-321.37**	**0.69**	0.88	0.98
Gait predictability (V)	<0.0001	1.88	-266.33	0.46	<0.0001	2.28	-311.17	0.51	**<0.0001**	**<0.0001**	**2.68**	**1.00**	**-316.22**	**0.52**	0.79	0.96
Gait predictability (ML)	<0.0001	2.74	-286.25	0.14	<0.0001	2.76	-299.66	0.17	**<0.0001**	**0.0017**	**2.72**	**2.32**	**-306.63**	**0.19**	0.66	0.93
Gait synchronization (AP-V)	<0.0001	2.10	-770.81	0.13	0.0076	2.13	-776.06	0.14	**<0.0001**	**0.0008**	**2.09**	**1.00**	**-779.08**	**0.15**	0.77	0.95

V = Vertical, ML = Medio Lateral, AP = Anterior Posterior.

Edf = Effective degrees of freedom. An *Edf*-value around 1 indicates a linear pattern, and values > 1 denote nonlinear patterns [27].

The adjusted r^2 represents the amount of variance explained by the model.

The *p*-value indicates whether the smooth is significantly different from zero.

The final model information, determined after model comparison, is presented in bold.

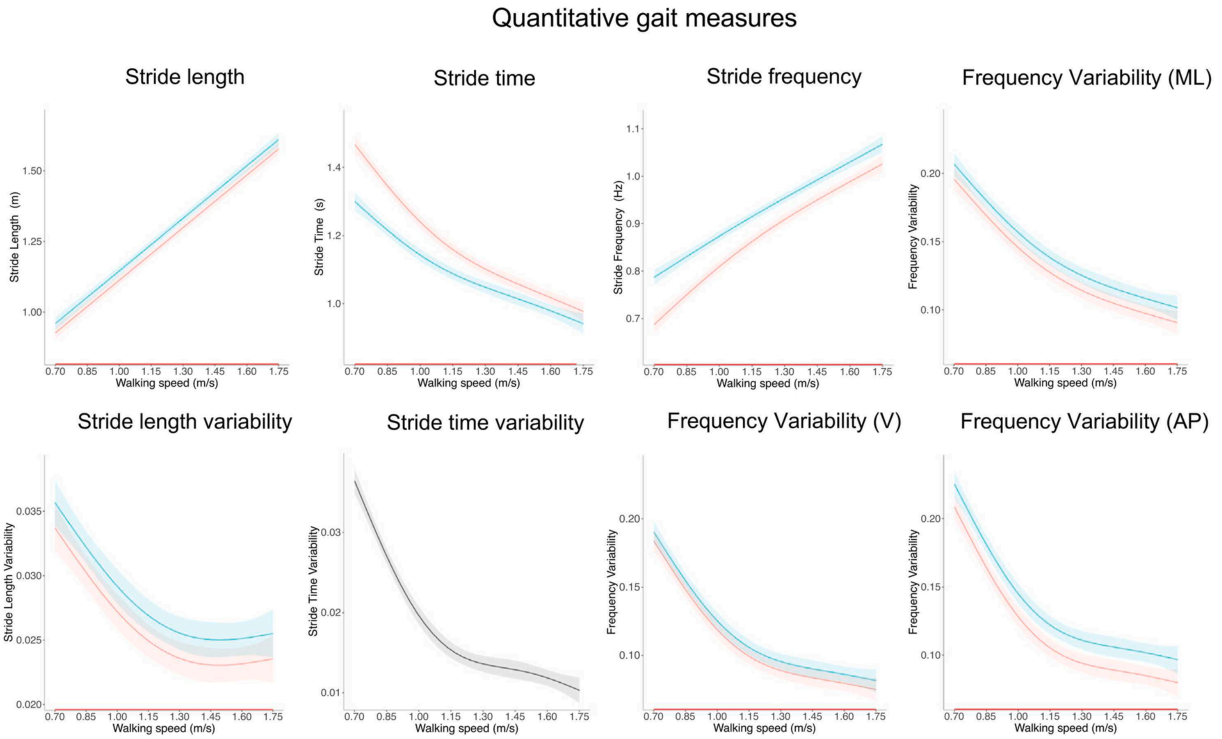

Fig. 1. Effects of age and walking speed (absolute) on quantitative gait measures. Bands around solid lines denote 95% confidence intervals. Red coloring of the x-axis denotes age group-differences. Turquois: young adults: Red: Older adults: Grey: Young and older adults.

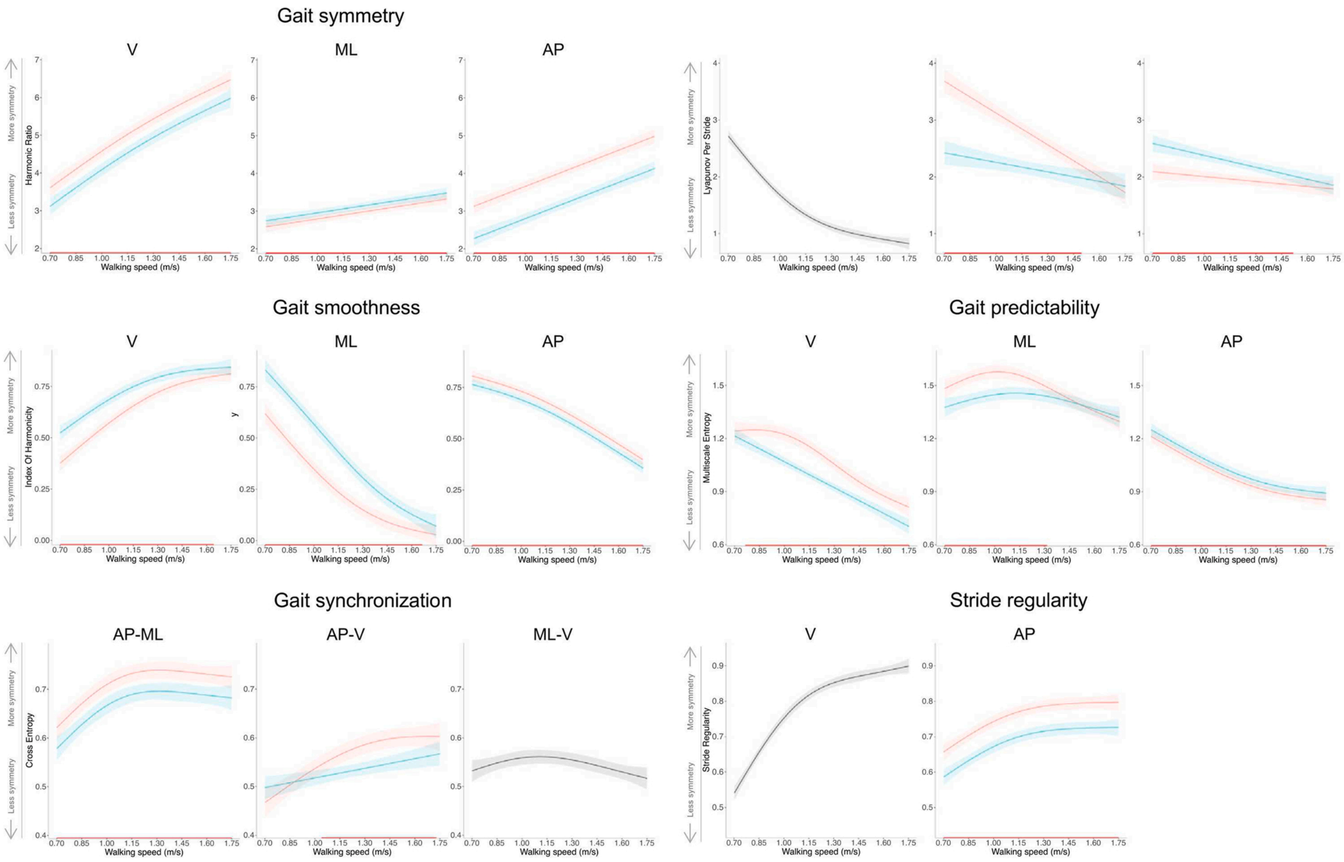

Fig. 2. Effects of age and walking speed (absolute) on qualitative gait measures. Bands around solid lines denote 95% confidence intervals. Red coloring of the x axis denotes age group-differences. Turquois: young adults: Red: Older adults: Grey: Young and older adults.

Table 4

Differences in final modaes of GAMM analyses on absolute speeds and relative speeds (treadmill and overground).

	Absolute speeds	*EDF all*	*EDF young*	*EDF old*	%PWS Treadmill	*EDF all*	*EDF young*	*EDF old*	%PWS Overground	*EDF all*	*EDF young*	*EDF old*
Spatiotemporal												
Stride length	Model2	1.00			Model1	2.70			Model2	2.73		
Stride time	Model3		2.75	2.53	Model3		2.8	72.78	Model3		2.82	2.65
Stride frequency	Model3		2.2	1.43	Model3		2.44	2.5	Model3		2.44	2.25
Gait variability												
Stride length variability	Model2	2.53			Model2	2.67			Model2	2.67		
Stride time variability	Model1	2.93			Model1	2.93			Model1	2.92		
Frequency variability (V)	Model2	2.86			Model2	2.87			Model1	2.83		
Frequency variability (ML)	Model2	2.62			Model2	2.81			Model2	2.68		
Frequency variability (AP)	Model2	2.88			Model2	2.85			Model2	2.83		
Gait quality												
Stride regularity (V)	Model1	2.91			Model2	2.91			Model1	2.91		
Stride regularity (AP)	Model2	2.5			Model2	2.63			Model2	2.5		
Gait stability (V)	Model1	2.88			Model2	2.91			Model1	2.9		
Gait stability (ML)	Model3		1.00	1.00	Model3		1.00	1.56	Model3		1.00	1.00
Gait stability (AP)	Model3		1.00	1.00	Model2	2.19			Model2	1.91		
Gait smoothness (V)	Model3		2.52	2.44	Model3		2.55	2.47	Model3		2.59	2.54
Gait smoothness (ML)	Model3		2.5	2.37	Model3		2.23	2.66	Model2	2.61		
Gait smoothness (AP)	Model2	2.34			Model1	1.00			Model2	2.64		
Gait symmetry (V)	Model2	1.73			Model2	2.38			Model2	1.00		
Gait symmetry (ML)	Model2	1.00			Model1	1.00			Model2	1.00		
Gait symmetry (AP)	Model2	1.00			Model2	1.00			Model2	1.00		
Gait synchronization (ML-V)	Model1	2.24			Model1	2.82			Model1	2.49		
Gait synchronization (AP-ML)	Model2	2.61			Model2	2.73			Model2	2.79		
Gait synchronization (AP-V)	Model3		2.09	1.00	Model3		2.24	2.48	Model3		2.42	1.88
Gait predictability (V)	Model3		2.68	1.00	Model2	2.67			Model2	1.00		
Gait predictability (ML)	Model3		2.72	2.32	Model3		2.39	1.00	Model3		2.86	1.91
Gait predictability (AP)	Model2	2.38			Model2	2.78			Model2	2.43		

V = Vertical, ML = Medio Lateral, AP = Anterior Posterior

Edf = Effective degrees of freedom. An *Edf*-value around 1 indicates a linear pattern, and values > 1 denote nonlinear patterns [27].

4. Discussion

We examined the relationship between walking speed and quantitative and qualitive gait outcomes in younger and older adults. As expected, gait measures were sensitive to walking speed but the type of relation with walking speed was outcome-dependent in younger and older adults.

Slower vs. faster walking was associated with shorter strides, longer stride times, and a lower stride frequency, with more variability in these spatiotemporal measures independent of age. For gait quality measures, in agreement with previous data [23], decreasing walking speed was associated with decreases in gait symmetry, stability and regularity in all directions. Speed-effects of gait smoothness were direction dependent, as it decreased in V direction, but increased in AP and ML directions with decreasing speeds. Additionally, gait predictability decreased (V, AP) and gait synchronization increased (AP-ML, AP-V) with decreasing walking speeds.

Overall, the relationship between walking speed and gait measures was characterized as linear or logarithmic, except for synchronization of trunk accelerations (ML-V) and gait predictability (ML), which showed a quadratic relationship. Although reported previously [13–15], for the majority of gait measures studied, we thus did not distinguish a clear optimum in the curves. The lack of quadratic relationships could be explained by the selection of fixed walking speeds for all participants, which ignores a person's PWS and their own sensitivity to walking speed [21]. However, expressing speeds relative to PWS, which ranged from ~30–140% for PWS overground and from ~40–120% for PWS treadmill, did not reveal a more prominent quadratic pattern (Appendix, Figs. 1–3). Furthermore, the logarithmic relationship with walking speed could also be explained by the range of walking speeds chosen. We assume that comfortable walking speed overground (Young: 1.55 $m \cdot s^{-1}$, Old: 1.55 $m \cdot s^{-1}$) represents PWS more accurately than PWS on a treadmill (Young:1.23 $m \cdot s^{-1}$, Old: 1.16 $m \cdot s^{-1}$) [30], which might be related to the way we determined PWS. The maximum attainable speed was 1.75 $m \cdot s^{-1}$ so that the faster speeds in this study were ~20% above PWS. Previous studies suggested that speed affects gait more prominently at speeds below or above 40% of PWS [14].

Gait synchronization (ML-V), stride time variability, gait stability (V) and stride regularity (V) were sensitive to speed, but not to aging (Model 1). Intercept differences between younger and older adults (Model 2), as we observed for stride length, stride length variability, stride regularity (AP), gait smoothness (AP), gait symmetry (V, ML, AP), stride frequency variability (V, ML, AP), gait synchronization (AP, ML) and gait predictability (AP), indicate that the type of relationship with walking speed is similar in both age groups, but age-related differences exist regardless of walking speed. Such intercept differences suggest that age-related differences in gait measures arise from other factors than walking speed. To illustrate, age-differences in gait stability, regardless of walking speed, were found to be partly be explained by declines in muscle strength and flexibility with aging [19]. Future studies should examine which factors account for the age-related differences regardless of walking speed for the gait quality measures studied here.

Differences in the type of the relationship with walking speed between younger and older adults, as we reported for stride time, stride frequency and several measures of gait quality, imply that the type of relationship with walking speed differs between the two age groups. For example, gait smoothness(V, ML) and gait predictability (ML), differed largely between younger and older adults at lower speeds, but differences leveled off at higher speeds. Furthermore, gait synchronization (AP-V) and gait predictability (V) were affected linearly by waking speed in older adults, but logarithmically in younger adults. Additionally, the decline in gait stability with decreasing speeds was more prominent in younger adults in ML direction, but more prominent in older adults in AP direction. This implies that age and walking speed have interactive effects on several gait measures. The majority of age-related differences in speed-effects remained similar when expressing speed relative to PWS, but we observed some differences in whether or not the age intercept was significant (Table 3). However, when model comparison revealed that the age intercept was significant, differences between younger and older adults were small (<10%). Therefore, we assume that abovementioned differences between absolute and relative speeds, are the result of unevenly spaced data, which is also indicated by the larger confidence intervals at both ends of the speed curves (Appendix, Figs. 1-3).

These results show that age-effects on the type of relationship with walking speed vary for gait measures, with either no differences between age-groups, age-related differences that exist regardless of speed, and age-related differences that occur in the type of relationship with walking speed. When studying the effects of age, we therefore support the use of gait measures that have a similar relationship with walking speed in both age groups (Model 2). These measures are preferred over those measures that are affected differently by walking speed in both age groups (Model 3) or those that are sensitive to speed but not to aging (Model 1). Abovementioned aging effects were found in relatively young (69.5 y) and fit (82% reached 1.75 $m \cdot s^{-1}$) individuals. A comprehensive assessment of the effects of walking speed in this group of older adults is important, since it provides information about differences that are already present in a relatively young and healthy group, while these differences might be enlarged when developing underlying impairments at a later age. It is expected that when testing older adults with underlying impairments, these age-effects will be even more prominent. Therefore, it is important to consider that walking speed may have a large influence on gait measures studied in these populations. To illustrate, several gait quality measures used in the current study have also been studied in the context of fall risk [7,31]. For the majority of gait measures, we observed more prominent speed effects below 1.20 $m \cdot s^{-1}$. As the PWS of fallers is generally below 1.20 $m \cdot s^{-1}$ and differs between people at a high or low risk for falls [7], walking speed may thus largely influence gait quality measures between fallers and non-fallers.

The explained variance of the final models was considerably higher for quantitative (76%) vs. qualitative measures (3%–69%). When adding random intercepts to the final model, the explained variance of gait quality measures increased considerably (Table 2), which indicates large inter-subject variability in these measures. It has been reported that age, height, and gender have negligible effects on gait quality measures such as step time asymmetry and gait irregularity [32]. This suggests that the observed heterogeneity in gait quality measures is caused by factors other than age, gender, or height. As adding factor smooths, which allow the type of relationship to vary across individuals, increased the variance only slightly more than random intercepts (Table 3), we assume that although there is large inter-subject variability in the intercept of gait quality measures, the type of relation between these measures and walking speed, is fairly consistent across individuals.

In the current study, participants walked on a treadmill. The disadvantage of treadmill testing is that it modifies walking because subjects have fewer options for altering gait kinematics from stride to stride [33]. The results of this study can therefore not be directly generalized to overground walking. However, for our aim, treadmill walking was more suitable than overground walking, since we could control speeds and compare groups at the same speeds. We fixed the order of walking speeds so that older adults could quit the experiment when they perceived that walking speed jeopardized safety. Between trials, participants were allowed to take rest to prevent fatigue and we found no evidence for fatigue to affect the data (Table 1). Therefore, we do not expect that the lack of randomization has affected our results. Beyond these limitations, the use of GAMMs in this study made it possible to examine whether gait measures were sensitive to speed, but also examine the type of relationship with walking speed. To conclude, the current study provides a comprehensive overview of the effects of walking speed on quantitative and qualitive gait measures in younger and older adults, and shows that the type of relationship with walking speed and the effects of age on this relationship, are outcome-dependent. Depending on the gait measure of interest, we found either no differences between age-groups, age-related differences that existed regardless of speed, and age-related differences in the type of relationship with walking speed. This implies, that for a proper evaluation of gait in older adults both speed and the type of outcome measure should be considered.

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Declaration of competing interest

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2022.01.001.

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