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Do spatiotemporal parameters and gait variability differ across the lifespan of healthy adults? A systematic review

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ABSTRACT

Background: Aging is often associated with changes in the musculoskeletal system, peripheral and central nervous system. These age-related changes often result in mobility problems influencing gait performance. Compensatory strategies are used as a way to adapt to these physiological changes.
Research question: The aim of this review is to investigate the differences in spatiotemporal and gait variability measures throughout the healthy adult life.
Methods: This systematic review was conducted according to the PRISMA guidelines and registered in the PROSPERO database (no. CRD42017057720). Databases MEDLINE (Pubmed), Web of Science (Web of Knowledge), Cochrane Library and ScienceDirect were systematically searched until March 2018.
Results: Eighteen of the 3195 original studies met the eligibility criteria and were included in this review. The majority of studies reported spatiotemporal and gait variability measures in adults above the age of 65, followed by the young adult population, information of middle-aged adults is lacking. Spatiotemporal parameters and gait variability measures were extracted from 2112 healthy adults between 18 and 98 years old and, in general, tend to deteriorate with increasing age. Variability measures were only reported in an elderly population and show great variety between studies.
Significance: The findings of this review suggest that most spatiotemporal parameters significantly differ across different age groups. Elderly populations show a reduction of preferred walking speed, cadence, step and stride length, all related to a more cautious gait, while gait variability measures remain stable over time. A preliminary framework of normative reference data is provided, enabling insights into the influence of aging on spatiotemporal parameters, however spatiotemporal parameters of middle-aged adults should be investigated more thoroughly.

1. Introduction

Gait is often used as a way to quantify physical function, quality of life and health status [1] since walking is one of the most frequently performed physical activities in daily life [2]. Changes in gait performance have been demonstrated to correlate with risk of falling [3], cognitive impairment (e.g. dementia) [4] or even risk of early mortality [5]. The ability to walk safely and efficiently is an important predisposition in maintaining independence with older age [6]. However, aging is associated with changes in the muscular, skeletal [7] and central/peripheral nervous systems [8,9]. Impairments such as loss of muscle strength [10] and proprioceptive feedback [11], but also deterioration of specific brain sites, for example in motor cortical regions [12] or the basal ganglia [13], related to normal aging can result in mobility problems and an increased risk of falling [14,15]. All of these age-related changes can influence gait performance. Compensatory strategies are observed to increase stability and prevent falls [16] as a way to adapt to the physiological changes that occur with aging. Elderly populations tend to develop a more cautious gait, which is commonly characterized by a reduced walking speed, reduced stride length and an increased step width [17]. Assessment of spatiotemporal gait parameters thus provides objective data of the global performance [18,19].

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More recently, the use of gait variability measures has increased since they may be more sensitive in quantifying age-related changes in the motor control of gait [8]. Gait variability measures seem to show an increase in variability with advancing age [20].

Most frequently, spatiotemporal parameters of healthy adults are used as control values in order to determine if a certain patient population diverts from the norm, for instance when investigating the influence of neurological [21,22], cardiovascular [23,24] or musculoskeletal impairments on gait [25,26]. On the other hand, spatiotemporal parameters of healthy adults have been used in order to investigate the influence of age on the way of walking. Most research focussing on the effect of aging on gait has been comparing younger with older adults [7] or different elderly populations with each other [1]. Therefore, an overview of the available literature concerning spatiotemporal parameters of adults of all ages can provide more transparency on the influence of aging on gait. Additionally, understanding the effect of aging on gait can provide important knowledge for clinicians on which gait characteristics are important for a safe, independent and efficient gait in elderly populations, and which could eventually provide guidelines for rehabilitation.

Furthermore, a recent review only discussed changes in a limited amount of spatiotemporal parameters in combination with changes in kinetics, kinematics and energy consumption with increasing age [27]. Other reviews investigated the changes in gait variability related to fear of falling [28] or analysed the differences in spatiotemporal parameters of elderly fallers and non-fallers [29], none discussing the changes in gait parameters with increasing age in healthy adults.

Therefore, the purpose of this systematic review is to investigate the differences in spatiotemporal and gait variability measures throughout healthy adult life, measured through an instrumented walkway during walking at a self-selected walking speed.

2. Methods

2.1. Protocol and registration

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis Statement (PRISMA). The protocol is available at PROSPERO (registration nr. CRD42017057720) and can be consulted online (www.crd.york.ac.uk/prospero/).

2.2. Systematic literature search

A systematic literature search, based on the Population Intervention Comparison Outcome (PICO) method, was conducted in March 2018 in MEDLINE (Pubmed), Web of Science (Web of Knowledge), Cochrane Library for clinical trials and ScienceDirect using combinations of the following keywords: 'Adult', 'Gait' and 'Spatiotemporal Parameters'.

No filters were applied. Specifics on the search queries for the different databases are available in Appendix 1 in Supplementary material.

2.3. Eligibility criteria & study selection

To select relevant literature, the following selection criteria were applied:

1 Participants were healthy adults aged 18 and older consisting of a combination of men and women, for which evidence had to be provided : at least a statement on known neurological, cardiovascular and musculoskeletal health, BMI $<$ 30, absence of any other impairments that can influence gait (e.g. visual or vestibular impairment). The samples had to be representative for the average population of healthy people. Therefore, studies investigating e.g. athletes, high-level sports participation, soldiers, one of the sexes exclusively were excluded from the sample. A minimum sample size of 30 participants was considered representative in accordance with the COnsensus-based Standards for the selection of health Measurement Instruments for identifying differences between relevant groups (hypothesis testing) [30].

2 Data must be collected during an instrumented overground gait analysis (e.g. GAITRite, force platforms, 3D gait analysis etc) while walking at a self-selected walking speed. Data collected using accelerometery were excluded as spatial variables and walking speed can be significantly underestimated [31]. Citations were excluded when data were collected during functional walking measures (e.g. Timed Up and Go, obstacle negotiation, climbing stairs, six-minute walk test); treadmill walking or during running, turning, stepping tasks (lateral, forward, backward, etc) or when slips/perturbations were induced.

3 Numeric values of mean spatiotemporal parameters (STP) or gait variability measures reported as primary outcome. When STP were reported for left and right separately, the results for the right side were extracted.

4 Original research, including full length articles and brief reports in which the applied methodology was reported transparently, written in English, French, Dutch or German. Reviews of any kind, meta-analyses, case studies/-series, conference proceedings, abstract only, books/book chapters, letter to the editor, study protocols, pilot studies, editorials or opinion pieces were excluded.

The selection process was conducted in two phases. In phase 1, the selection criteria were applied on the citations' title and abstract. If a study met these criteria or its eligibility could not be determined from the title and abstract, it was selected on full-text screening (phase 2) using the same eligibility criteria. After phase two, references of all included studies were screened, and included if eligible, to ensure that no relevant articles were missed. The selection process was performed by two independent reviewers (NH, EV). The selection process is presented in Fig. 1.

2.4. Risk of bias

Risk of bias was not assessed, as for now no assessment tool for identifying risk of bias regarding normative data is available. Bias was addressed by applying rigorous selection criteria, taking representativeness of the study sample and sample size (selection bias) into account.

2.5. Data extraction

Data were extracted by two reviewers (NH, EV) and summarized in a methodology and evidence table. The methodology table summarizes information on study design, type of instrumented walkway, walkway length, footwear, study sample characteristics such as number of participants, age (min, max, mean and standard deviation (SD)), sex distribution (number of women), body mass index (BMI, mean and SD), body length (mean and SD) and origin.

The primary outcome measures were means and standard deviations of either spatiotemporal parameters or gait variability measures, which were plotted according to age. When results for comparable groups were available, e.g. men and women or separate groups receiving a different type of intervention but with controlled sample characteristics, a weighted mean was calculated based on the raw (baseline) data.

Outcome measures reported as step width, stride width and base of support were combined into one measure: step width, as they all reported a similar distance between the two feet in medio-lateral direction. If necessary, units were converted to from cm/s to m/s for gait speed; cm to m for spatial parameters and ms to s for temporal parameters. Applied definitions for the extracted STP are presented in

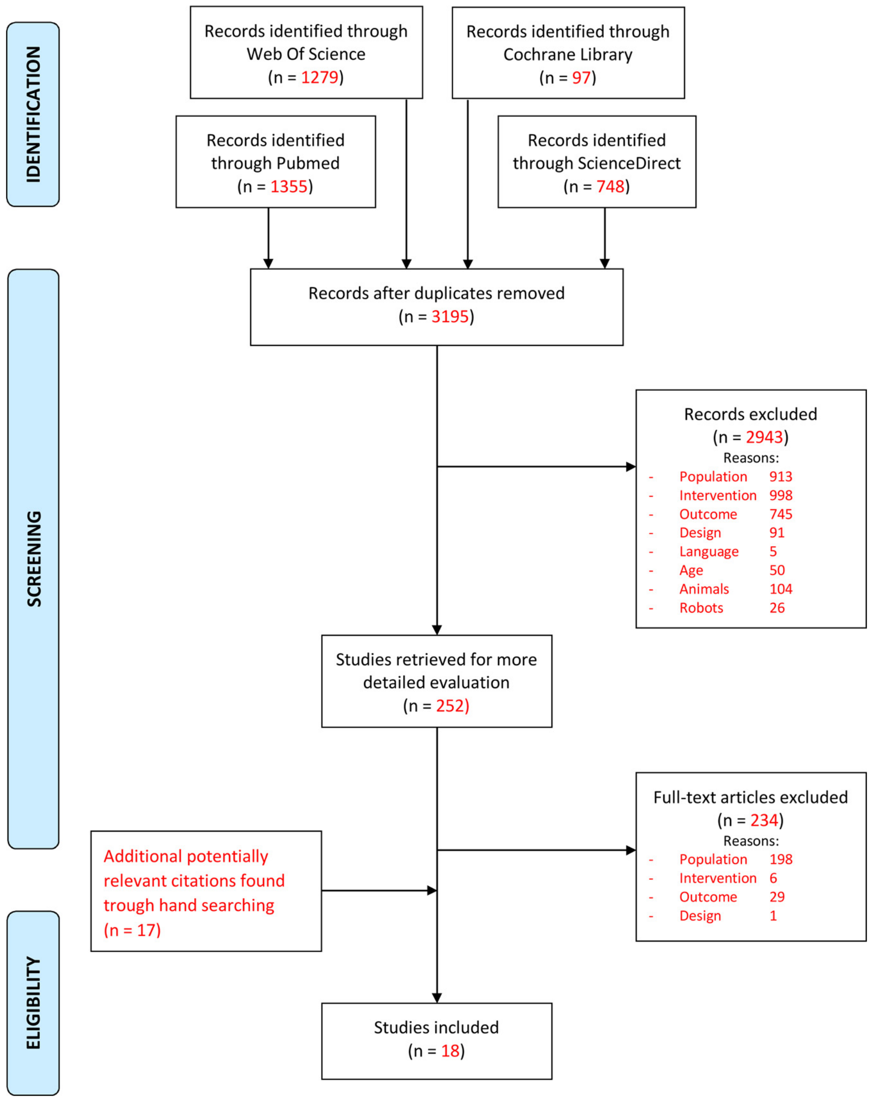

Fig. 1. Flowchart of the selection process.

Appendix 2 in Supplementary material.

3. Results

3.1. Search results

In total, 3195 original studies were identified from the electronic databases MEDLINE (Pubmed), Web of Science (Web of Knowledge), Cochrane Library and ScienceDirect after deduplication. After screening on title and abstract, 252 were deemed potentially relevant and were taken to screening phase two. After a more detailed screening of the full text, 18 of the 252 studies met the eligibility criteria and were included in this review. No additional studies were included after hand searching the references of the included articles. The selection process is presented in Fig. 1.

3.2. Study characteristics

Data were extracted from 2112 healthy adults (1131 women, 53.6%) between 18 [32] and 98 [33] years old. Seven included studies reported the STP or variability measures of a young adult population (aged 19–40) [32,34–39], ten studies of an elderly population (aged 65 and up) [1,33,40–47] and one study compared a young adult population with an elderly population [48]. Specifics on the sample characteristics are provided in Table 1.

Mean and variability measures were collected through the GAITRite system (n = 8 [1,32–34,40–43];), OptoGait system (n = 1 [35];), Gait Mat system (n = 1 [44];), Vicon motion analysis system (n = 5 [36–39,46];), a Selspot II optoelectric system (n = 1 [48];), a BTS 3D GA system (n = 1 [47];) and a 3D – Motion Analysis Corporation system (n = 1 [45];). Gait parameters were all measured during over ground walking on a walkway varying from 4.60 to 30 m in length, at a self-selected walking speed. Only four studies reported if the subjects walked barefoot [35,42,44] or wearing shoes [43] (Table 1).

3.3. Differences in spatiotemporal parameters as a function of age

Numeric values for mean STP and gait variability are presented in Tables 2a, 2b and 3 respectively. Graphical presentation of the STP as a function of age are presented in Fig. 2 (mean values) and 3 (gait variability).

3.4. Spatial parameters

A total of 12 references included in this review reported spatial parameters. *Step length* was reported in eight of the included articles and ranged from 0.711 m ± 0.011 m in 60-year-olds [43] to 0.495 ± 0.079 m in 90-year-olds [33]. *Stride length* decreased from

Table 1
Characteristics of the individual studies.

Author	Design	Type of instrumented walkway	Walkway length (m)	Footwear	Study sample characteristics										
					# Subjects	*# Women*	*Age (years)*				*BMI (kg/m²)*		***Length (m)***		***Origin***
							Min	*Max*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	
Beauchet et al. 2017	CS[a]	GaitRite	4.60-7.90		954	437	65	> 85	72.8	4.8	26.2	4.1			International[c]
Chui et al. 2010	CS	Gaitrite	4.6		118	83	72	98	84.8[b]	5.3[b]	29.66[b]	3.67[b]			USA
Delbaere et al. 2009	CS	Gaitrite	7.2		44	27			76.8	5.2			1.68	0.09	Australia
Dujmovic et al. 2017	CC	Gaitrite	5.5		40	26			39.4	15.3					Serbia
Elboim-Gabyzon et al. 2017	CS	Gaitrite	/	barefoot	47	34			76.7	7.7	26.7	4.8	1.60	0.10	Israel
Gomez Bernal et al. 2016	CS	Opto gait	10	barefoot	126	85			27.4	1.8	22.69	2.56	1.68	0.04	Spain
Hollman et al. 2011	CS	Gaitrite	5.6		294	186	70	89	79	5	26.69	4.15	1.66	0.06	USA
Jenkins et al. 2009	CC	Gaitrite	6	shoes	40	25	49	77	64.7	7.7					USA
Khashan et al. 2014	CC	Gait Mat system	/	barefoot	40	14			64.9	10.2	26.4	3.8	1.68	0.08	Israel
Kodesh et al. 2015	CS	Gaitrite	5.17		40	25	18	40	26	4.7			1.69	0.10	Israel
Lee et al. 2017	CS	3D - Motion Analysis Corporation, Santa Rosa,	30		30	15			74.1	7.6			1.61	0.08	South Korea
McClelland et al. 2011	CC	3D - Vicon	10		40	22			69.6	8.3			1.65	0.09	Australia
McGibbon et al. 2003	CC	3D - Selspot II optoelectric system	10		45	29			29.7	6.9	24.08	3.43	1.68	0.09	USA
					37	24			71.2	8.2	25.27	4.43	1.64	0.09	
Meldrum et al. 2014	CS	3D - Vicon	10		30	18			30	6.8	22.6		1.70		Ireland
Pistacchi et al. 2017	CC	BTS 3D GA system	10		44	22			67.0	9.4					Italy
Sturnieks et al. 2008 (b)	CC	3D - Vicon	/		42	17	24	56	37.6	7.5			1.74	0.08	Australia
Sturnieks et al. 2008 (a)	CC	3D - Vicon	10		47	18	23	56	38.2	7.9	24.9	3.6	1.74	0.09	Australia
Yang et al. 2016	CS	3D - vicon	14		54	27			23.9	4.7			1.67	0.10	USA

Legend: Data presented as Mean (SD); CS: Cross-sectional study design; CC: Case-control study design; m: meters.
[a] combination of different cross-sectional studies.
[b] Weighted mean.
[c] data from Australia, Belgium, Canada, France, Japan, Luxembourg, Norway, USA, and Switzerland.

Table 2a
Overview of the mean spatio-temporal and spatial gait parameters.

Author	Population Characteristics					Spatio-temporal parameters				Spatial parameters (m)					
	# Subjects	Age (years)				Walking speed (m/s)		Cadence (steps/min)		Step length		Stride length		Step width	
		min	max	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Beauchet et al. 2017	711			70.60	2.40	1.25	0.22					1.380	0.166	0.099	0.031
	207			77.60	2.60	1.14	0.24					1.265	0.197	0.096	0.032
	36			87.70	2.80	0.89	0.18					1.029	0.153	0.100	0.032
Chui et al. 2010	19	70	79			1.39	0.24	120.23	11.88	0.689	0.088	1.380	0.175	0.095	0.025
	77	80	89			1.13	0.10	111.89	3.91	0.604	0.043	1.210	0.086	0.110	0.013
	22	90	99			0.87	0.17	103.58	7.31	0.495	0.079	0.994	0.158	0.109	0.033
	118	70	99	84.80	5.30	1.13	0.09	111.68	3.69	0.597	0.038	1.197	0.076	0.108	0.011
Delbaere et al. 2009	44			76.90	5.10	1.09		106.41		0.590				0.096	
Dujmovic et al. 2017	40			39.40	15.30	*1.39*	*0.978 - 1.638*					*1.406*	*1.110 - 1.686*		
Elboim-Gabyzon et al. 2017	47			76.70	7.70	0.99	0.03	111.10	1.60			1.055	0.022		
Gomez Bernal et al. 2016	126			27.37	1.77	1.30	0.10	115.62	6.41	0.681	0.040	1.358	0.080		
Hollman et al. 2011	60	70	74			**1.17**	**0.18**	**108.05**	**14.60**	**0.646**	**0.086**	**1.302**	**0.157**	**0.082**	0.033
	107	75	79			**1.15**	**0.16**	**111.76**	**12.16**	**0.615**	**0.070**	**1.233**	**0.142**	**0.080**	0.043
	80	80	84			**1.06**	**0.16**	**106.76**	**8.54**	**0.596**	**0.075**	**1.203**	**0.154**	**0.094**	0.041
	47	85	89			**0.99**	**0.21**	**106.21**	**10.30**	**0.555**	**0.093**	**1.099**	**0.189**	**0.093**	0.033
Jenkins et al. 2009	40			64.73	7.66	1.31	0.03			0.711	0.011				
Kashan et al. 2014	40			64.90	10.20	1.08	0.18	109.70	9.70	0.591	0.071	1.179	0.142		
Kodesh et al. 2015	40	18	40	26.00	4.70	1.35	0.06								
Lee et al. 2017	30			74.07	4.14			105.61	5.46			1.072	0.156	0.151	0.021
McClelland et al. 2011	40			69.60	8.30	1.27	0.18	121.60	7.10			1.250	0.180		
McGibbon et al. 2003	45			29.70	6.90	1.32	0.16			0.674	0.058			0.109	0.041
	37			71.10	8.20	1.16	0.18			0.601	0.081			0.106	0.038
Meldrum et al. 2014	30			30.00	6.80	1.40	0.09	122.00	4.27	0.690	0.002	1.380	0.050	0.140	0.020
Pistacchi et al. 2017	44			67.00	9.42	1.33	0.06	113.84	4.30						
Sturnieks et al. 2008 (b)	42	24	56	37.60	7.50	1.50	0.17					1.490	0.170	0.070	0.047
Sturnieks et al. 2008 (a)	47	23	56	38.20	7.90	1.41	0.21	116.20	15.60			1.490	0.170	0.070	0.090
Yang et al. 2016	54			23.90	4.70	1.41	0.20								

Legend: underlined values = converted values (cm to m and ms to s); *italic values* = median values and interquartile range; **bold values** = weighted mean; m: meters; s: seconds; steps/min: steps per minute.

1.406 m in 30-year-olds [34] to 0.994 m ± 0.158 m in 90-year-olds [33]. *Step width* was reported to be lowest in 30-year-olds at 0.070 m ± 0.047 m [37] and highest in 70-year-olds at 0.151 m ± 0.021 m [45]. However, a great variability in reported step width is noted in the elderly population. In general step- and stride length tend to decrease with increasing age, whereas step width tends to remain stable over time (Fig. 2). Significant differences were found for step length and stride length with increasing age in elderly populations aged 65 to 85 and older ($p < 0.001$) [40], when comparing 70–74 and 75–79 year-olds to elderly aged 80 and older ($p < 0.001$) [1] or in elderly aged 70–98 ($p \leq 0.006$) [33]. However, no significant differences in step width were found regardless of the age groups investigated [1,40].

3.5. Temporal parameters

Temporal parameters were reported in ten of the included references. *Step time* and *stride time* both show an increase with increasing age as step and stride time were lowest for 30-year-olds at 0.50 s ± 0.02 s and 0.99 s ± 0.03 s [36] and highest in 80-year-olds at 0.57 s ± 0.06 s [1] for step time and 1.18 s ± 0.14 s [40] for stride time. *Stance time* ranged from 0.66 s ± 0.07 s in 20-year-olds [48] to 0.78 s ± 0.11 s in 80-year-olds [40], the same is noted for *single support time* as 70-year-olds are reported to have a single support time of 0.42 s ± 0.04 s [40], while 20-year-olds were reported to have a single support time of 0.33 s ± 0.03 s [39]. *Swing time* also increased from 0.36 s ± 0.02 s in 20-year-olds [35] to 0.42 s ± 0.04 s in 70-year-olds [40]. For *double support time*, 30-year-olds showed a double-limb support time of 0.19 s ± 0.02 s [36] which increased to 0.38 s ± 0.10 s in 80-year-olds [40]. In general, temporal parameters show an increase when comparing young adults with elderly, while within the elderly population temporal parameters stay fairly consistent.

However, some results are not in line with results reported by Beauchet et al. [40] as they reported a significant decrease of swing ($p = 0.049$) and single-limb support times ($p = 0.021$) between elderly groups ranging between 65 and 85 years of age. Stride time, stance time and double-limb support time increased with age ($p < 0.001$) and were in line with the other results found in this review (Fig. 2). On the other hand, Hollman et al. [1] did not find any significant differences in temporal parameters between age groups in an elderly cohort ranging from 70 years to 85 + years of age, except for double-limb support time between 70–74 and 85–89 year-olds ($p < 0.05$) and 75–79 and 85–89 year-olds ($p < 0.01$).

3.6. Combined parameters

Combined parameters walking speed and cadence were reported in 17 of the studies included in this review. The walking speed of 30-year-olds was noted to be the highest at 1.50 m/s ± 0.17 m/s [37] and decreased with time to 0.87 m/s ± 0.17 m/s in 90-year-olds [33]. The same shift can be noted for c*adence* as in 90-year-olds cadence was reported to be 105.58 ± 7.32 steps/min [37], while 30-year-olds displayed the highest cadence at 122.00 ± 4.27 steps/min [33]. McGibbon et al. [48] compared 20-year-olds with 70-year-olds and found a significant decrease in gait speed between these two groups ($p < 0.05$). Hollman et al. [1] and Chui et al. [33] both investigated differences within an elderly population and both found a significant decrease in mean walking speed between elderly age-groups ($p < 0.001$). However, cadence was not significantly decreased ($p = 0.051$) in the investigated age-groups of Hollman et al. [1] but did significantly decrease ($p < 0.001$) in the cohort of Chui et al. [33].

Table 2b
Overview of the mean temporal gait parameters and percentage of the gait cycle.

Author	Population characteristics					Temporal parameters (s)												Gait phases (%)							
	# Subjects	Age (years)				Step time		Stride time		Stance time		Single Support time		Swing time		Double Support time		Stance		Single Support		Swing		Double Support	
		min	max	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Beauchet et al. 2017	711			70.60	2.40			1.12	0.12	0.70	0.09	0.42	0.04	0.42	0.04	0.28	0.06								
	207			77.60	2.60			1.13	0.18	0.71	0.09	0.41	0.04	0.41	0.04	0.31	0.07								
	36			87.70	2.80			1.18	0.14	0.78	0.11	0.40	0.04	0.40	0.04	0.38	0.10								
Chui et al. 2010	19	70	79															62.91	1.22	74.21	2.47	37.10	1.22	25.81	2.41
	77	80	89															63.69	0.81	72.65	1.63	36.32	0.81	27.45	1.56
	22	90	99															65.31	1.88	69.42	3.72	34.71	1.88	30.77	3.75
	118	70	99	84.80	5.30													63.86	0.69	72.30	1.38	36.15	0.69	27.80	1.38
Delbaere et al. 2009	44			76.90	5.10											0.31									
Dujmovic et al. 2017	40			39.40	15.30			1.13	0.92 - 1.22					0.39	0.33 - 0.45	0.25	0.16 - 0.43								
Elboim-Gabyzon et al. 2017	47			76.70	7.70																			28.70	0.61
Gomez Bernal et al. 2016	126			27.37	1.77	0.53	0.03	1.05	0.05	0.69	0.04	0.36	0.02	0.36	0.02	0.33	0.03								
Hollman et al. 2011	60	70	74			**0.56**	**0.06**	**1.11**	**0.11**	**0.71**	**0.09**	**0.41**	**0.05**	**0.41**	**0.04**	**0.30**	**0.06**	**63.26**	**2.65**	**37.05**	**2.57**	**36.60**	**2.11**	**26.76**	**3.55**
	107	75	79			**0.54**	**0.06**	**1.08**	**0.11**	**0.68**	**0.07**	**0.39**	**0.05**	**0.39**	**0.04**	**0.30**	**0.05**	**63.93**	**2.86**	**36.14**	**3.93**	**36.27**	**2.58**	**35.06**	**5.25**
	80	80	84			**0.57**	**0.05**	**1.13**	**0.09**	**0.72**	**0.07**	**0.40**	**0.04**	**0.40**	**0.04**	**0.32**	**0.06**	**64.18**	**2.65**	**36.02**	**2.31**	**36.01**	**2.64**	**28.26**	**4.65**
	47	85	89			**0.57**	**0.06**	**1.14**	**0.12**	**0.74**	**0.1**	**0.41**	**0.04**	**0.41**	**0.04**	**0.33**	**0.08**	**64.62**	**2.56**	**35.55**	**2.59**	**35.52**	**2.63**	**29.18**	**4.41**
Jenkins et al. 2009	40			64.73	7.66							0.41	0.03												
Kashan et al. 2014	40			64.90	10.20													60.5	1.7	39.40	1.20	39.50	1.70	21.20	2.70
Lee et al. 2017	30			74.07	4.14															35.15	3.53				
McGibbon et al. 2003	45			29.70	6.90					0.66	0.07														
	37			71.10	8.20					0.68	0.06														
Meldrum et al. 2014	30			30.00	6.80	0.50	0.02	0.99	0.03			0.40	0.02			0.19	0.02								
Sturnieks et al. 2008 (a)	47	23	56	38.20	7.90					0.67	0.06														
Yang et al. 2016	54			23.90	4.70			1.06	0.10			0.33	0.03			0.20	0.03								

Legend: underlined values = converted values (cm to m and ms to s); *italic values* = median values and interquartile range; **bold values** = weighted mean; s: seconds.

Table 3
Overview of gait variability measures.

Author	Population characteristics					Gait Variability (coefficient of variation. %)													
	# Subjects	Age (years)				CoV Step length		CoV stride length		CoV BoS		CoV stride time		CoV Swing time		CoV Stance time		***CoV DS time***	
		Min	Max	Mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	*mean*	*SD*
Beauchet et al. 2017	711			70.60	2.40			2.20	1.10	24.60	34.70	2.10	1.10	4.00	1.70	3.10	1.30	6.80	2.90
	207			77.60	2.60			2.60	1.30	33.00	82.60	2.30	1.10	4.50	1.70	3.20	1.50	6.30	2.50
	36			87.70	2.80			3.60	2.10	28.20	23.40	2.80	1.30	6.00	2.70	3.50	1.70	6.00	2.10
Dujmovic et al. 2017	40			39.40	15.30			2.20	1.00 - 6.82			2.23	1.20 - 11.08	4.38	2.69 - 18.63			9.78	4.48 - 34.09
Hollman et al. 2011	60	70	74			**6.31**	**9.40**	**3.56**	**3.08**	**3.27**	**2.31**	**3.72**	**3.14**	**5.44**	**6.77**	**5.34**	**4.49**		
	107	75	79			**5.62**	**5.94**	**4.56**	**5.32**	**3.12**	**2.33**	**4.81**	**6.20**	**7.38**	**9.02**	**5.47**	**5.63**		
	80	80	84			**5.53**	**2.75**	**4.07**	**2.05**	**3.46**	**2.73**	**3.89**	**1.90**	**5.69**	**2.20**	**5.02**	**2.95**		
	47	85	89			**6.08**	**2.70**	**5.35**	**4.60**	**2.94**	**1.13**	**5.02**	**4.82**	**8.18**	**10.21**	**5.51**	**3.74**		

Underlined values = converted values (cm to m and ms to s); *italic values* = median values and interquartile range; **bold values** = weighted mean.

3.7. Gait cycle phases

Only three of the included references reported gait cycle percentages. In an elderly population, an increase in *stance* and *double support phase* is noted: 62.91% ± 1.22% and 25.81% ± 2.41% in 70-year-olds, to 65.31% ± 21.88%–30.77% ± 1.38% in 90-year-olds respectively [33]. The *swing phase* tends to decrease when comparing 70-year-olds to 90-year-olds (37.10% ± 1.22%–34.71% ± 1.88%), as did the *single-limb support*. However, single-limb support percentages varied greatly, as Chui et al. [33] reported the mean single-limb support of both legs combined, ranging between 74.21% ± 2.47–69.42% ± 3.72 in 70 to 90-year-olds ($p < 0.05$), while Hollman et al. [1] reported a single-limb support for one leg, ranging between 36.60% ± 2.11% for 70-year-olds to 35.52% ± 2.63% for 80-year-olds but these differences were not significant ($p > 0.05$).

3.8. Gait variability measures

Gait variability measures were expressed as coefficients of variation (CoV; (SD/mean)*100) and were almost exclusively reported in an

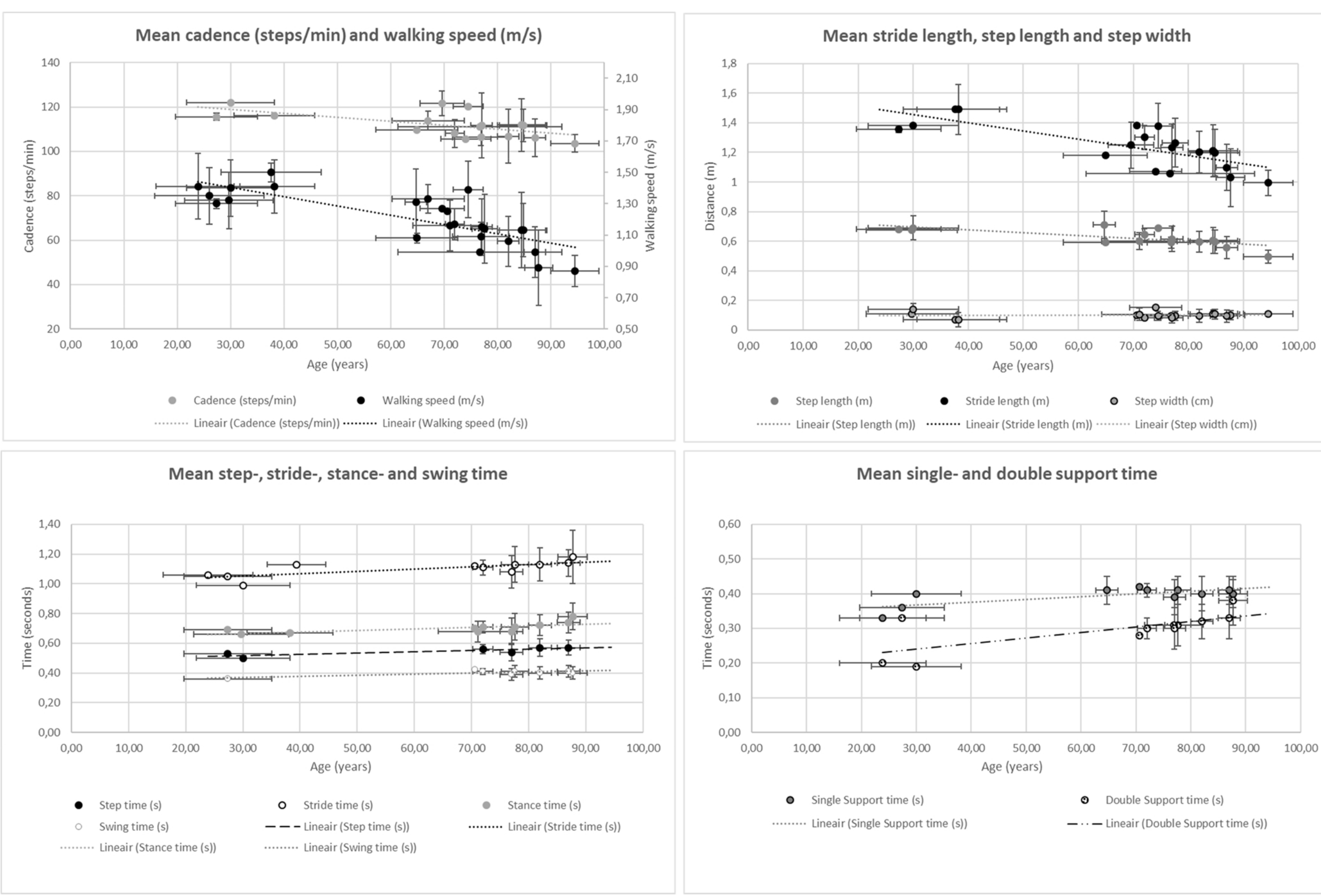

Fig. 2. Overview of the mean step-time parameters as a function of age.
Dots are mean values; error bars represent SD of age (horizontal) or of the selected parameter (veritcal).

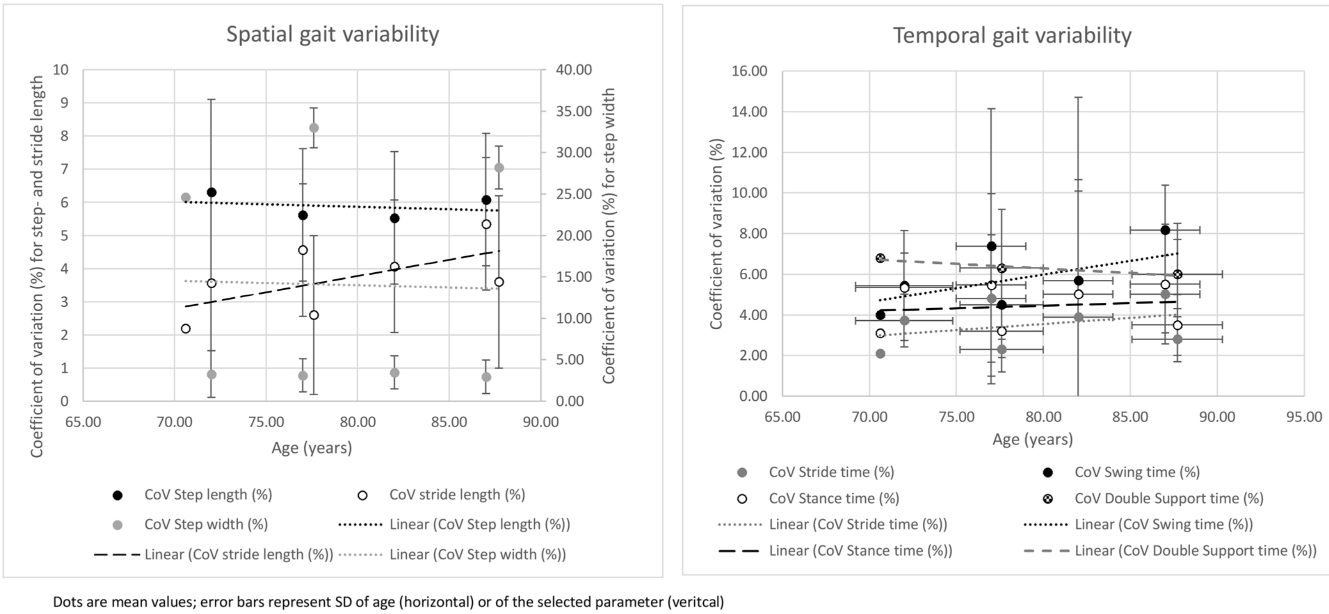

Fig. 3. Gait variability as a function of age.
Dots are mean values; error bars represent SD of age (horizontal) or of the selected parameter (veritcal).

elderly population ranging from 70 years to 89 years of age. *Step length* and *double-limb support time CoV* show a decrease with increasing age (6.31% ± 9.40% to 6.08% ± 2.70% and 9.78% to 6.00% ± 2.10% respectively [1,40]), while *stride time CoV* (2.23% to 5.02% ± 4.82%) and *swing time CoV* (4.38% to 8.18% ± 10.21%) show an increase with increasing age [1,34]. *Step width* and *stance time CoV* remain fairly stable in an elderly population. However, values between studies seem to differ widely (Fig. 3). Hollman et al. [1] did not find any significant age-effects, however Beauchet et al. [40] did find significant age effects except for double-limb support time CoV (p = 0.186).

4. Discussion

The purpose of this systematic review was to describe the differences in spatiotemporal and gait variability measures throughout healthy adult life, measured through an instrumented walkway, during walking at self-selected walking speed. In total, 23 unique spatio-temporal and gait variability measures were identified in the currently included literature, gathered through an instrumented walkway or a 3D-motion analysis system. Overall findings of this literature review are: 1) most mean spatiotemporal parameters of gait seem to be affected by age, 2) mean step width and variability measures seem to remain stable over time, 3) most of the reported data are based on an elderly population above the age of 65, followed by the young adult population, while data from the middle-aged adult population is lacking and 4) variability measures are only reported in an elderly population and show a great variety between studies.

The data presented in this study are based on healthy adults without any musculoskeletal, cardiovascular or neurological impairments. These strict selection criteria were defined as these comorbidities may impose important changes to the way of walking [21,24,49]. Because of these rigorous criteria, the presented data represent the effect of aging without the influence of multimorbidities that often co-occur with aging [50,51], allowing a solid basis towards identifying gait deviations. The small amount of included papers is therefore not surprising. Although a large set of studies is available on “healthy” adults that include people that are free of any neurological, musculoskeletal or orthopedic impairments, evidence of cardiovascular health is often lacking. However, cardiovascular health also plays an important role in functioning, which is shown by altered gait patterns, e.g. in patients with intermittent claudication a slower walking speed, shorter step length and lower cadence is noted [23]. The results in this review therefore additionally provide a preliminary framework of normative reference data that enables insights into the influence of aging on STP, however data of middle-aged adults is lacking.

4.1. Age-related differences in mean STP

In general, the results of this systematic review indicate a reduction of gait performance with increasing age as spatial and spatio-temporal parameters tend to decrease while temporal parameters tend to increase. These features seem to suggest that as people grow older, they develop a cautious gait pattern, characterized by decreased walking speed, cadence, step length and stride length and increased step time, stride time and phases.

Walking speed, the most reported spatiotemporal parameter, declines with increasing age. This may be the result of the short step and stride lengths noticed in an elderly population, which in its turn may be the result of weakened hip extensors and ankle plantar flexors reducing the capacity to propel the body forwards [52]. A decreased walking speed may also be the result of balance impairments [53] which results in a more cautious gait [29,54]. This cautious gait can also be noted in the differences of the temporal parameters across age groups with increasing age, which may be the result of lower limb muscle weakness [55,56] or might be a compensatory strategy used to increase weight-bearing stability during gait [2]. However, when looking at the differences in step width and gait cycle percentages, these remain fairly stable throughout the different age-groups as only small differences are noted with increasing age.

4.2. Age-related differences in gait variability

Measures related to gait variability in the included literature were almost exclusively reported in an elderly cohort above the age of 70 and, in general, remained fairly stable. Age-related differences in spatial and temporal variability measures may be elicited by a loss of lower extremity strength and range of motion, increased muscle activation variation and changes in balance [9,57]. These differences in balance can be the result due to a decline in central motor control, worsening of the automatic stepping mechanism [8] or an insufficient postural stability in general, related to older age [3]. As stated by Dingwell et al. [58], aged healthy adults implement the same underlying stride-to-stride control strategies as young adults do. However, due to physiological changes neuromotor noise is increased, which in its turn results in a greater variability even though healthy elderly are just as successful in reducing the effect of input noise. On the other hand, as stated by Hausdorff et al. [20], gait variability measures may be able to reveal increased variability or instability even when the subsystem that contributes to gait variability only shows subtle changes.

4.3. Limitations of the study

Some limitations are to be considered. First, no risk of bias assessment was performed on the included references as only data from healthy control groups were extracted and implemented in this review for which an assessment tool is still lacking. Instead, selection criteria were defined in such a way that bias could be accounted for, without using a dedicated assessment tool. Additionally, strict selection towards methods on data-collection of STP were addressed as well, as the purpose of this review was not report the effect if interventions or specific walking tasks on STP.

Secondly, a lack of information regarding cardiovascular, musculoskeletal or neurological health of the healthy adult population resulted in the exclusion of several studies reporting spatiotemporal parameters or gait variability measures.

4.4. Implications for future research and clinical relevance

Clearly, data on middle-aged people are lacking. This suggests that future research is necessary to fill the existing gap regarding normative reference values for STP in gait in the middle-aged population. Additionally, a broad range in spatiotemporal parameters is available with a high covariance among these measures which may indicate redundancy [59]. One method to narrow the range of different gait characteristics and increase transparency is to cluster the different characteristics in components of gait through a principal component analysis, as suggested by Lord et al. [59]. These domains of gait could provide a comprehensive but flexible approach to assessment as the selection of gait characteristics will depend on the gait pathology. However, in general these (mean) spatiotemporal parameters are a quick and easy way to quantify gait performance.

On the other hand, consensus regarding the methods used to analyse gait variability is lacking [60]. Articles included in this review only reported variability as the coefficient of variation, while variability also can be reported as standard deviation (SD). Lord et al. [60] suggest the use of SD to report gait variability as it provides more clarity as opposed to the coefficient of variation which is a composed parameter which can be influenced by either the mean or the standard deviation. Clearly, the exact meaning of variability measures remains to be determined as well as how variability should be expressed.

5. Conclusion

The findings from this systematic review suggest a deterioration in walking in elderly populations, shown by the differences in spatiotemporal and gait variability measures. However, additional research is necessary in middle-aged adults from the age of 30 up to the age of 59 to be able to determine when these differences start to appear and to be able to fully understand the effects of aging on gait.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2018.06.012.

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