



Critical spatiotemporal gait parameters for individuals with dementia: A systematic review and meta-analysis

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Instrumented gait analysis allows for the identification of walking parameters to predict cognitive decline and the worsening of dementia. The aim of this study was to perform a meta-analysis to better clarify which gait parameters are affected or modified with the progression of the dementia in a larger sample, as well as which gait assessment conditions (single-task or dual-task conditions) would be more sensitive to reflect the influence of dementia. Literature searches were conducted with the keywords “quantitative gait” OR “gait analysis” AND “dementia” AND “single-task” AND “dual-task,” and for “quantitative gait” OR “gait analysis” AND “dementia” AND “fall risk” on PubMed, EMBASE, the Cochrane Library, Scopus, and Web of Science. The results were used to perform a systematic review focussing on instrumental quantitative assessment of the walking of patients with dementia, during both single and dual tasks. The search was performed independently by two authors (C. R. and C. M.) from January 2018 to April 2020 using the PICOS criteria. Nine publications met the inclusion criteria and were included in the systematic review. Our meta-analysis showed that during a single task, most of the spatiotemporal parameters of gait discriminated best

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between patients with dementia and healthy controls, including speed, cadence, stride length, stride time, stride time variability, and stance time. In dual tasks, only speed, stride length, and stride time variability discriminated between the two groups. In addition, compared with spatial parameters (e.g. stride length), some temporal gait parameters were more correlated to the risk of falls during the comfortable walking in a single task, such as cadence, stride time, stride time variability, and stance time. During a dual task, only the variability of stride time was associated with the risk of falls.

Keywords: Gait; analysis; dementia; task performance; falls.

Introduction

Motor and cognitive functions share neuroanatomical structures and psychological processes.^{1,2} Therefore, people with dementia not only have memory and cognitive dysfunctions, but also movement and executive disorders, which seem to follow a retrograde progression, according to the phenomenon of “retrogenesis.”³

Observational gait analyses of patients with dementia grossly show slowness, static and dynamic instability, abnormal posture, and a wide basis of support. Instrumented gait analysis using optoelectronic systems or wearable technology allows for a more precise estimation of dementia-related modifications in walking.^{4,5}

Some studies suggest that modifications of gait parameters are relevant for predicting cognitive decline and the worsening of dementia, and this information could be used to develop specific interventions to prevent further functional decline and falls, as well as to follow rehabilitation progress of patients.^{4,5} In addition, specific profiles of gait impairment have been related to the stage and type of cognitive impairment.⁶ Therefore, instrumented gait analysis seems to be a useful tool for obtaining more specific and subclinical information about the progression of dementia.

Performing dual tasks could modify the postural balance and the fluidity of gait. Thus, modifications of the gait characteristics of patients with dementia could be used to identify those who are suffering from deficient executive function and a higher risk of falls.^{7,8} Furthermore, gait analysis could provide an early assessment of the risk of falls and of the dynamic instability, especially during the execution of dual tasks.^{9–11}

The most frequently analyzed spatiotemporal parameters in the current literature are related to variables reflecting gait rhythm, pace, and variability.^{4,5,12–18} The parameters reflecting gait

rhythm are temporal variables of the duration of gait phases relative to the gait cycle, such as the swing time, stance time, stride time, and cadence. The pace domain includes parameters related to walking speed and displacement in the sagittal plane, such as gait speed and stride length.

Gait variability (CV) is measured as the coefficient of variance and is defined as the fluctuation in spatiotemporal characteristics between steps. Gait variability is a sensitive indicator of mobility deficits and risk of falls.¹⁹ The parameters most used for gait variability in the current literature are stride length CV, swing time CV, and stance time CV.^{4,5,14,15,18}

However, kinetic and kinematic data have been studied less, due to the technical difficulties in obtaining recordings from patients. In this regard, only a few studies have been devoted to investigating the kinematic data in terms of joint excursions of the hip, knee, and ankle.^{20,21}

We systematically reviewed the literature on gait analysis and dementia from January 2003, when the last review on the same topic was performed,²² to April 2020. In this period, several studies were examined both walking alone (single task)^{4,5,12–18} and walking while performing another action (dual task).^{4,12–14,17} More recently, spatiotemporal parameters assessed by gait analysis under dual-task conditions were introduced. In the review from 2003,²² only one article evaluated the effect of performing dual task among seven people with dementia.

The dual-task condition could be used as a screening tool for detecting Alzheimer’s dementia at an early stage,⁴ although other studies and clinical trials are needed. However, it is not fully understood which gait parameters are actually correlated to dementia and can be considered as predictive signs of cognitive decline and worsening of disease.

Therefore, the aim of this study was to perform a meta-analysis to better clarify which gait

parameters are affected or modified with the progression of the disease in a larger sample, as well as which gait assessment conditions (single-task or dual-task conditions) are more sensitive to reflect the influence of dementia. All of this information could be interesting for both to identifying gait abnormalities and developing specific rehabilitation interventions to better control postural instability and reduce the risk of falls.

Methods

Search strategy

A search was performed on the following electronic medical databases: PubMed, EMBASE, the Cochrane Library, Scopus, and Web of Science. The reference lists of the related articles were also used to search for other eligible papers. The search strategy was conducted from January 2018 to April 2020. We searched for the following terms and keywords: “quantitative gait” OR “gait analysis” AND “dementia” AND “single-task” AND “dual-task,” and for “quantitative gait” OR “gait analysis” AND “dementia” AND “fall risk.”

Selection criteria and data extraction

From 2003 to 2020, the database searches yielded 751 references from the first search, 1426 from the second search, and 71 from the third research. The titles and abstracts of these studies were screened and 209 selected papers remained for full text screening. The eligibility of the studies for inclusion was assessed independently.

Nine publications met the inclusion criteria and were included in the meta-analysis, and 187 articles were excluded for the following reasons: 24 examined neurological disorders other than dementia or the diagnosis of dementia, 89 were on preclinical stages of dementia and mild cognitive impairment, 28 did not include gait analysis as an instrumental assessment, and 46 presented results that were not useful for the meta-analysis (Fig. 1). We included original articles published in English about gait analysis on subjects with a confirmed diagnosis of dementia who underwent gait analysis obtained by instrumented systems (i.e. electronic walkways, wearable sensors, and stereophotogrammetric systems). We excluded animal studies and those regarding preclinical stages of dementia and mild cognitive impairment.

We included studies that compared mild cognitive impairment with dementia. Furthermore, studies were excluded if they had participants with

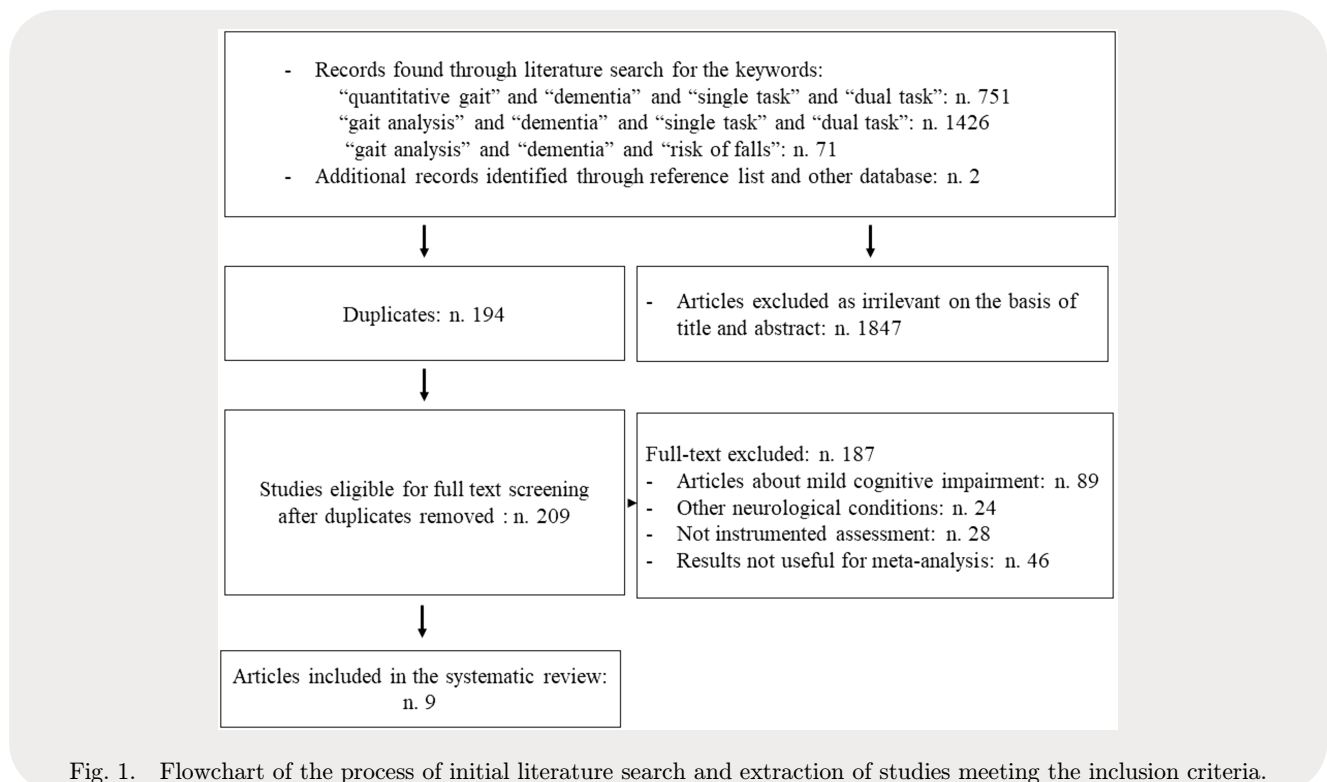


Fig. 1. Flowchart of the process of initial literature search and extraction of studies meeting the inclusion criteria.

other neurological diseases and comorbidity gait disorders (e.g. Parkinson’s disease). The other exclusion criteria were the use of qualitative results and arbitrary units, such as symmetry and regularity, and the use of statistical values without the mean values of each parameter, that is, we excluded articles that did not provide data useful for the meta-analysis (i.e. the mean and standard deviation). We also excluded all of the duplicate studies and unpublished data.

Our meta-analysis focussed on gait parameters that were reported in more than one article.

We included studies that investigated the abnormal parameters in gait analysis in people with dementia conditions, including Alzheimer’s disease,^{4,5,12–16} frontotemporal dementia,¹⁷ and other types of dementia, such as vascular dementia.^{5,18}

In order to identify the eligible studies, the reviewers (C. R. and C. M.) independently screened the titles and abstracts from the initial search. In cases of conflicting opinions, consensus was reached after discussion between the authors. Selected full texts were then reviewed and included in the systematic review in accordance with the PRISMA protocol,²³ the MOOSE checklist,²⁴ and the PICOS²⁵ (population, intervention, comparison, outcome, and study design) criteria. As shown in Table 1, the participants were aging adults; the interventions were based on rehabilitation in dementia; and comparator could be any comparator. The outcomes included clinical assessments, diagnostic scales, and gait analysis parameters, and the study designs were RCTs and observational studies.

The gait data were obtained during the first evaluation (at zero time) of comfortable walking, without assistive devices or other signs and symptoms, such as extra-pyramidal signs, which could have influenced gait performance. The gait data included spatiotemporal gait variables such as gait speed, step length, stride length, stride length CV, and cadence, as well as stability parameters such as swing, stance time, and CVs of stance and swing time.

Allali *et al.*¹⁷ compared gait parameters of a group of patients with Alzheimer disease with a group of healthy controls. They also compared a group of patients affected by frontotemporal dementia with a control group. Both samples were analyzed separately and assessed twice in the meta-analysis. Lin *et al.*⁴ and Muir *et al.*¹⁴ assessed gait with some additional cognitive tasks. The dual-task condition used by Lin *et al.*⁴ consisted of walking while counting backwards by one and

counting forward, whereas Muir *et al.*¹⁴ used naming animals, counting backwards by one and counting backwards by seven. In our study, we assessed gait parameters under different dual-task conditions and analyzed the results of these authors separately.^{4,14}

Meta-analysis calculations

The Statistical Package for Social Sciences (SPSS, Version 18.0 for Windows; SPSS Inc., Chicago, IL, USA) was used for data analysis. The outcomes were considered as continuous data measured on the same scale expressed as a mean value and standard deviation (SD) and analyzed using standard mean differences (SMDs). We verified the impact of study heterogeneity on the results of the meta-analysis using the I^2 test for inconsistency (percentages and p -values under 0.05 were considered significant). An I^2 value $< 25\%$ was considered to indicate low risk of heterogeneity. A value between 25% and 50% was considered indicative of a moderate level of heterogeneity, and $> 50\%$ was considered to indicate statistical significance between the included studies.²⁶ A random-effect model was used to estimate the combined effect sizes (for each study, a study-specific true effect was estimated, while redistributing the study weights, from larger to smaller studies).²⁷ We calculated the sample-weighted pooled correlation coefficient for the meta-analysis with the random-effects model based on the moderate heterogeneity found in each study. A Forest plot was generated to depict the SMD along with the 95% confidence interval (95% CI) for each study, and the pooled mean difference was obtained by combining all studies.

The scale recommended by the Cochrane Collaboration²⁵ was used to assess the methodological quality of the identified studies and the risk of bias of the individual studies included. The major criteria of the checklist were randomization, double blinding (both the patients and the researchers/assessors), comparability of groups, and availability of follow-up information. Publication bias was also examined using funnel plots, to examine the symmetry of study effect-size variation around a meta-analytic effect size (asymmetry can indicate bias).

A sensitivity analysis was conducted for each study individually to evaluate the quality and consistency of the results. For consistency with the

Table 1. Demographic characteristics of patients with dementia: Review of the studies.

Study	Study design	No. of pt, type of dementia	Mean age \pm SD	Instruments	Single-task parameters	Dual-task parameters	Dual task
Allali <i>et al.</i> ¹⁷	Cross-sectional study	19 AD	76.3 \pm 8.9	SMTEC system	Speed	Speed	CB
		22 HC	71.0 \pm 0.5		Stride time	Stride time	
Allali <i>et al.</i> ¹⁷	Cross-sectional study	19 FTD	62.1 \pm 9.6	SMTEC system	Speed	Speed	CB
		22 HC	71.0 \pm 0.5				
Allali <i>et al.</i> ⁵	Cross-sectional study	177 AD	83.9 \pm 5.6	GAITRite system	Speed	Speed	CB3, CF3
		91 HC	83.3 \pm 5.2		Stride time CV Stance time Stride length Stride length CV Swing time Swing time CV		
Gillain <i>et al.</i> ¹²	Case-control study	6 AD	73.6 \pm NS	Locometrix system	Speed	Speed	CB
		14 HC	73.5 \pm NS		Stride length	Stride length	
Lin <i>et al.</i> ⁴	Case-control study	10 AD	74.0 \pm 8.6	Vicon MX system	Speed	Speed	CB, CF
		10 HC	73.8 \pm 6.1		Cadence Stride time Stride time CV Stride length Stride length CV	Stride time CV Stride length Stride time	
Maquet <i>et al.</i> ¹³	Case-control study	6 AD	74.0 \pm 4.0	Locometrix system	Speed	Speed, Stride length	CB
		14 HC	74.0 \pm 5.0		Stride length		
Muir <i>et al.</i> ¹⁴	Case-control study	23 AD	77.5 \pm 5.0	GAITRite System	Speed	Speed	NA, CB, CB7
		22 HC	71.0 \pm 5.0		Stride time Stride time CV	Stride time CV Stride time	
Van Lersel <i>et al.</i> ¹⁵	Case-control study	39 D NOS	78.3 \pm NS	Not specified electronic walkway	Speed		
		46 HC	73.8 \pm NS		Stride time CV Stride length CV		
Verghese <i>et al.</i> ¹⁸	Cohort study	12 AD	82.6 \pm 5.7	GAITRite system	Speed		
		17 VD	78.9 \pm 4.7		Cadence		
		4 D NOS			Stance time		
		36 HC			Stride length Stride length CV Swing time Swing time CV		
Webster <i>et al.</i> ¹⁶	Case-control study	10 AD	77.6 \pm 5.7	GAITRite system	Speed		
		10 HC	72.4 \pm 6.5				

Notes: D NOS, dementia not otherwise specified; AD, Alzheimer's disease; FTD, frontotemporal dementia; VD, vascular dementia; HC, healthy controls; N, number; Pt, patients; CF, counting forward; CB, counting backward; CB7, counting backwards by sevens; CB3, counting backwards by 3 digits; CF3, counting forward by 3; NA, naming animals; SD, standard deviation; CV, variability; NS, not specified.

primary objective, we focussed on quantitative gait analysis and dementia when the information was explicitly disclosed in the publications. $p < 0.05$ was considered to indicate a statistically significant difference.

Results

Description of the studies

The numbers of studies yielded at each stage of the search of the systematic review are shown in Fig. 1. A total of nine studies were included in the meta-analysis. The sample characteristics and details of the designs of each included study are displayed in Table 1.

Characteristics of patients

All study groups were homogeneous for general clinical features, such as age, clinical presentation, and duration of disease (Table 1). There was variation in other features, such as the duration of the disease, the electronic devices, and the kinds of gait parameters used.

There were four case-control studies,^{4,12,14,15} one cohort study,¹³ three cross-sectional studies,^{5,17,28} and one longitudinal prospective study.¹⁶

Type of dementia

The analysis assessed different types of dementia. There was no homogeneity among the types of dementia and the severity. Lin *et al.*⁴ and Maquet *et al.*¹³ assessed subjects with mild Alzheimer's disease. Allali *et al.*,⁵ Gillain *et al.*,¹² and Muir *et al.*¹⁴ reported about patients with moderate Alzheimer's disease. Webster *et al.*¹⁶ assessed patients with mild-to-moderate Alzheimer's disease. Another recent study by Allali *et al.*¹⁷ considered patients with moderate frontotemporal dementia and moderate-to-severe Alzheimer's disease. In the study by Verghese *et al.*,¹⁸ patients were affected by mild (62%), moderate (35%), and severe (2%) dementias.

According to several studies, there was a direct relationship between the severity of dementia and the presence of gait abnormalities in cases of Alzheimer's disease,^{4,5,12-16} frontotemporal dementia,¹⁷ and other types of dementia, including vascular dementia.^{5,18} Most of the studies focussed on the interaction of Alzheimer's disease and gait

analysis,^{4,5,12-16} and two of them compared people with moderate dementia to healthy controls.^{15,16} Four studies additionally examined the differences in gait pattern between people with Alzheimer's disease and those with mild cognitive impairment and healthy controls.^{5,12-14} Another study compared gait parameters in dementia-free people at baseline and after developing dementia.¹⁸

Because of the heterogeneous clinical presentation of the different types of dementia, as well as the difficulty in defining the characteristics of gait for each type, it could be important to identify which parameters are specific for both the kind of dementia and the disease stage.

Gait parameters

There was no homogeneity among the studies reporting gait parameters in cases of dementia. The most frequently studied spatiotemporal parameters, such as speed, made the results of the meta-analysis more accurate, whereas the less reported parameters, such as cadence, increased the difficulty of relating consistent findings.

Significant differences in spatiotemporal parameters of people with dementia with respect to healthy people during a single task of comfortable walking were evident in the decreases of gait speed ($n = 9$),^{4,5,12-18} cadence ($n = 2$),^{4,18} stride time ($n = 3$),^{4,14,17} and stance time ($n = 2$).^{5,18} However, stride time CV ($n = 4$),^{4,5,14,15} stride length CV ($n = 4$),^{4,5,15,18} and swing time CV ($n = 2$)^{5,18} were increased.

During dual tasks, gait parameters were different for reduced speed ($n = 5$)^{4,12-14,17} and increased stride time ($n = 3$)^{4,14,17} and stride time CV ($n = 2$).^{4,14} Stride length was examined in five studies for a single task^{4,5,12,13,18} and in three studies for dual-task conditions.^{4,12,13} Overall, the spatiotemporal parameters were significantly reduced, except in two studies that reported insignificant differences.^{12,13}

According to four investigations, temporal domains such as cadence, stride time, stride time variability, and stance time were more affected dementia-related gait parameters than spatial parameters (e.g. stride length).²⁹⁻³² Impairment in the ability to maintain a steady gait, with minimal stride-to-stride variations, was closely related to instability and fall risk and was independent of gait speed.³² In addition, two studies^{29,32} highlighted that a dual-task activity, such as walking while

Table 2. The effect of dementia on gait parameters during single-task condition.

Study	Type of D	Speed (m/s)	Cadence (steps/min)	Stride time (s)	Stride time CV (%)	Stance time (s)	Stride length (cm)	Stride length CV (%)	Swing time (s)	Swing time CV (%)
Allali <i>et al.</i> ¹⁷	AD	110.6 ± 9.9		1.1 ± 0.1						
Allali <i>et al.</i> ¹⁷	FTD	118.5 ± 9.0		1.2 ± 0.1						
Allali <i>et al.</i> ⁵	AD	61.8 ± 20.3			5.7 ± 4.1	0.9 ± 0.1	79.6 ± 20.3	7.1 ± 4.0	0.40 ± 0.1	0.001 ± 9.9
Gillain <i>et al.</i> ¹²	AD	102.0 ± 36.0					113.0 ± 45.0			
Lin <i>et al.</i> ⁴	AD	90.0 ± 30.0	97.0 ± 17.2	1.3 ± 0.2	5.2 ± 1.9		110.0 ± 20.0	6.7 ± 5.3		
Maquet <i>et al.</i> ¹³	AD	74.0 ± 26.0					100.0 ± 42.0			
Muir <i>et al.</i> ¹⁴	AD	110.8 ± 13.7		1.0 ± 1.1	2.6 ± 1.0					
Van Lersel <i>et al.</i> ¹⁵	D NOS	61.0 ± 30.0			5.0 ± 2.3			6.5 ± 2.2		
Vergheze <i>et al.</i> ¹⁸	AD VD D NOS	79.5 ± 23.0	95.3 ± 11.8			0.8 ± 0.1	99.3 ± 33.0	5.56 ± 2.4	0.45 ± 0.1	0.04 ± 2.0
Webster <i>et al.</i> ¹⁶	AD	102.0 ± 30.0								
<i>p</i>		< 0.001	< 0.001	0.014	< 0.001	0.023	< 0.001	0.048	0.568	0.047

Notes: D, dementia; FTD, frontotemporal dementia; AD, Alzheimer's disease; D NOS, dementia not otherwise specified; VD, vascular dementia; s, seconds; m, meters; CV, coefficient of variation; cm, centimeters; min, minutes.

reciting random numbers or counting down numbers, exhibited a greater risk of falls and increased variability of stride time, which is a temporal measure that is associated with fall risk.^{29,32}

Meta-analysis of gait parameters

The data showed that patients with dementia generally had the following gait features: slower gait speed and cadence, reduced stride time and stance time, shorter stride length, and greater stride time CV and stride length CV than healthy

elderly subjects. Tables 2 and 3 show what gait parameters provided significantly better discrimination between people with dementia and healthy controls during a single task or dual task. During single tasks, these parameters were speed, cadence, stride length, stride time CV ($p < 0.001$), stride time, stance time, and stride length CV ($p < 0.05$). During dual tasks, the parameters were stride time CV ($p < 0.001$) and stride length ($p < 0.05$). In contrast, we did not observe significant differences for swing time and swing time CV during a single task or for stride time during a dual task

Table 3. The effect of dementia on gait parameters during dual-task condition.

Study	Type of D	Dual task	Speed (m/s)	Stride time CV (%)	Stride length (m)	Stride time (s)
Allali <i>et al.</i> ¹⁷	AD	CB	88.9 ± 10.0			1.3 ± 0.2
Allali <i>et al.</i> ¹⁷	FTD	CB	89.4 ± 10.0			1.3 ± 0.2
Gillain <i>et al.</i> ¹²	AD	CB	74.0 ± 26.0		1.0 ± 0.4	
Lin <i>et al.</i> ⁴	AD	CB	80.0 ± 4.0	5.8 ± 5.0	1.0 ± 0.3	1.4 ± 0.4
Lin <i>et al.</i> ⁴	AD	CF	70.0 ± 3.0	9.9 ± 3.8	1.0 ± 0.3	1.5 ± 0.4
Maquet <i>et al.</i> ¹³	AD	CB	74.0 ± 26.0			
Muir <i>et al.</i> ¹⁴	AD	CB	96.4 ± 22.8	4.8 ± 2.7		1.0 ± 0.2
Muir <i>et al.</i> ¹⁴	AD	NA	81.0 ± 24.7	9.0 ± 8.9		1.2 ± 0.3
Muir <i>et al.</i> ¹⁴	AD	CB7	67.9 ± 28.5	12.4 ± 12.3		1.1 ± 0.6
<i>p</i>			< 0.001	< 0.001	0.040	0.067

Notes: D, dementia; FTD, frontotemporal dementia; AD, Alzheimer's disease; ±, standard deviation; NA, naming animals; CB, counting backwards by ones; CB7, counting backwards by sevens; CF, counting forward; s, seconds; m, meters; CV, coefficient of variation.

Table 4. Forest plot illustrating the effect of dementia on single-task speed when compared with cognitively healthy controls.

Study	Type of D	N	HC	N	D	Mean HC	Mean D	SMD	SE	95% CI		Weight (%)		Heterogeneity	
										Lower limit	Upper limit	Random	Fixed	Q	DF
										t	P	Random	Fixed	Q	DF
Allali <i>et al.</i> ¹⁷	AD	19	22	118.5 ± 11.7	110.6 ± 9.9	0.719	0.317	0.077	1.36	10.60	8.01	10.60	8.01	DF	9
Allali <i>et al.</i> ¹⁷	FTD	19	22	118.5 ± 11.7	111.8 ± 9.0	0.636	0.315	0.001	1.273	10.62	8.12	10.62	8.12	Significant level	$p < 0.0001$
Allali <i>et al.</i> ⁵	AD	177	91	104.7 ± 22.2	61.7 ± 20.3	1.987	0.155	1.683	2.292	11.92	33.70	11.92	33.70	I^2	86.93%
Gillain <i>et al.</i> ¹²	AD	6	14	140.0 ± 13.0	102.0 ± 36.0	1.161	0.502	0.106	2.215	8.70	3.20	8.70	3.20	95% CI for I^2	77.93–92.26
Lin <i>et al.</i> ⁴	AD	10	10	150.0 ± 20.0	90.0 ± 30.0	2.254	0.557	1.083	3.424	8.14	2.60	8.14	2.60		
Maquet <i>et al.</i> ¹³	AD	6	14	130.0 ± 14.0	74.0 ± 26.0	2.302	0.592	1.058	3.547	7.79	2.30	7.79	2.30		
Muir <i>et al.</i> ¹⁴	AD	23	22	135.7 ± 24.0	110.8 ± 13.7	1.245	0.321	0.597	1.892	10.57	7.82	10.57	7.82		
Van Lersel <i>et al.</i> ¹⁵	D NOS	39	46	65.0 ± 31.0	61.0 ± 30.0	0.130	0.216	-0.299	0.560	11.50	17.29	11.50	17.29		
Verghese <i>et al.</i> ¹⁸	AD VD	33	36	94.1 ± 23.6	79.5 ± 23.0	0.630	0.244	-0.133	1.107	11.27	13.53	11.27	13.53		
	D NOS														
Webster <i>et al.</i> ¹⁶	AD	10	10	140.0 ± 20.0	102.0 ± 30.0	1.427	0.484	0.410	2.444	8.89	3.44	8.89	3.44		
Total fixed effects		342	287			1.180	0.089	1.004	1.357	13.148	<0.001	100.00	100.00		
Total random effect		342	287			1.188	0.271	0.656	1.720	4.384	<0.001	100.00	100.00		

Notes: D, dementia; FTD, frontotemporal dementia; AD, Alzheimer's disease; D NOS, dementia not otherwise specified; VD, vascular dementia; HC, healthy controls; N, number; ±, standard deviation; SE, standard error; SMD, standardized mean difference; CI, confidence intervals; I^2 , inconsistency.

Table 5. Forest plot illustrating the effect of dementia on dual-task speed when compared with cognitively healthy controls.

Study	Type of D	Dual task	N	HC	N	AD	Mean HC	Mean AD	SMD	SE	95% CI		Weight (%)		Heterogeneity	
											Lower limit	Upper limit	Fixed	Random	Q	DF
											T	P	Fixed	Random	Q	DF
Allali <i>et al.</i> ¹⁷	AD	CB	19	22	102.3 ± 12.4	88.9 ± 10.0	1.176	0.333	-1.830	-0.484	17.62	14.12	17.62	14.12	DF	8
Allali <i>et al.</i> ¹⁷	FTD	CB	19	22	102.3 ± 12.4	89.4 ± 10.0	1.132	0.331	-1.783	-0.445	17.82	14.13	17.82	14.13	Significant level	$p < 0.0001$
Gillain <i>et al.</i> ¹²	AD	CB	6	14	130.0 ± 14.0	74.0 ± 26.0	2.302	0.661	-4.343	-1.567	5.58	12.29	5.58	12.29	I^2	88.91%
Lin <i>et al.</i> ⁴	AD	CB	10	10	140.0 ± 3.0	80.0 ± 4.0	16.252	2.605	-21.725	-10.779	0.29	2.74	0.29	2.74	95% CI for I^2	81.16–93.47
Lin <i>et al.</i> ⁴	AD	CF	10	10	130.0 ± 3.0	70.0 ± 3.0	19.153	3.058	-25.579	-12.727	0.21	2.10	0.21	2.10		
Maquet <i>et al.</i> ¹³	AD	CB	6	14	130.0 ± 14.0	74.0 ± 26.0	2.302	0.661	-4.343	-1.567	5.58	11.98	5.58	11.98		
Muir <i>et al.</i> ¹⁴	AD	CB	23	22	129.0 ± 27.0	96.4 ± 22.8	1.279	0.323	-1.929	-0.628	18.84	12.29	18.84	12.29		
Muir <i>et al.</i> ¹⁴	AD	NA	23	22	122.9 ± 30.4	81.0 ± 24.7	1.495	0.332	-2.159	-0.818	17.71	14.18	17.71	14.18		
Muir <i>et al.</i> ¹⁴	AD	CB7	23	22	115.9 ± 25.4	67.9 ± 28.5	1.749	0.346	-2.438	-1.044	16.35	14.12	16.35	14.12		
Total fixed effects			139	158			1.545	0.140	1.269	11.036	<0.001	100.0	100.0			
Total random effects			139	158			2.377	0.477	1.439	4.985	<0.001	100.0	100.0			

Notes: D, dementia; FTD, frontotemporal dementia; AD, Alzheimer's disease; HC, healthy controls; N, number; ±, standard deviation; SE, standard error; SMD, standardized mean difference; CI, confidence intervals; I^2 , inconsistency; NA, naming animals; CB, counting backwards by ones; CB7, counting backwards by sevens; CF, counting forward.

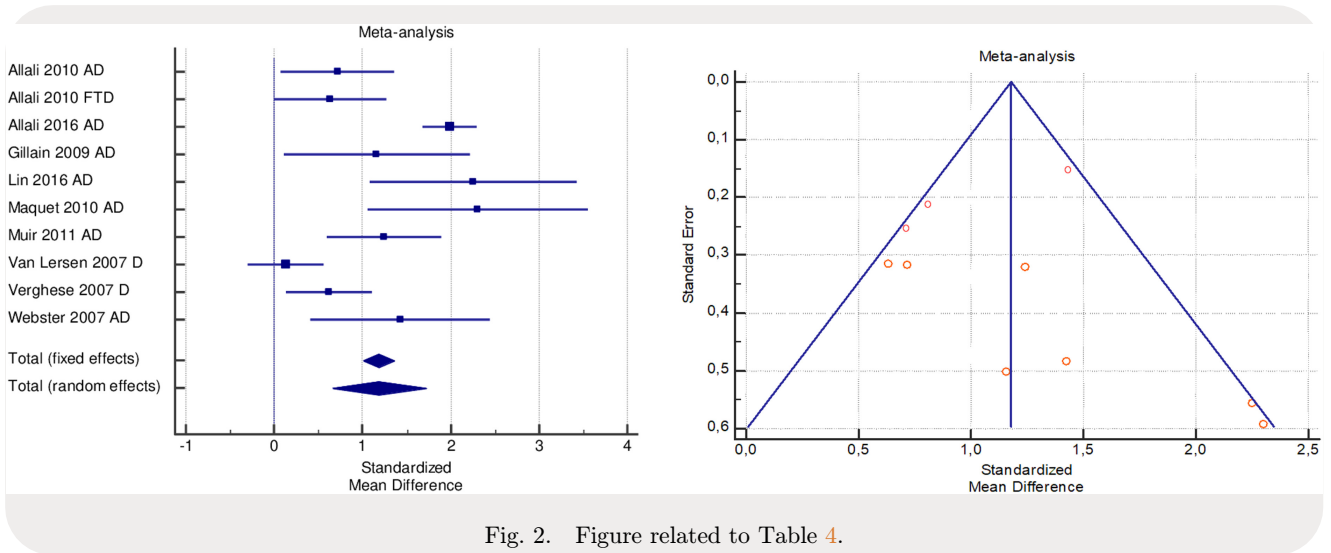


Fig. 2. Figure related to Table 4.

($p > 0.05$). Tables 4 and 5 show that speed, one of the parameters more frequently reported, discriminates significantly between dementia and healthy controls in both single and dual tasks ($p < 0.001$) (Figs. 2 and 3).

Heterogeneity and publication bias

The heterogeneity between studies was high (I^2 between 86.93 and 88.91%), as shown in Tables 4 and 5. The funnel plot (Figs. 2 and 3) showed that there was symmetry between the studies, and no significant publication bias was seen. However, there was a small study effect, but it was insignificant. The sensitivity analysis also showed the absence of an excessive influence of individual studies.

Discussion

Summary of collected data

To our knowledge, this is the only systematic review in the last 15 years that provides a comprehensive overview and meta-analysis of studies devoted to a quantitative evaluation of gait dysfunctions in dementia, including Alzheimer's disease and frontotemporal and vascular dementia. During single and dual tasks, dementia is associated with impairment of gait speed, cadence, and stride length, but not swing time, and these data are significant even in the presence of a high CV.

The prevalence of mobility dysfunction, motor impairments, and falls is higher in people with dementia than cognitively healthy older adults. Gait abnormalities have been reported in 16% and

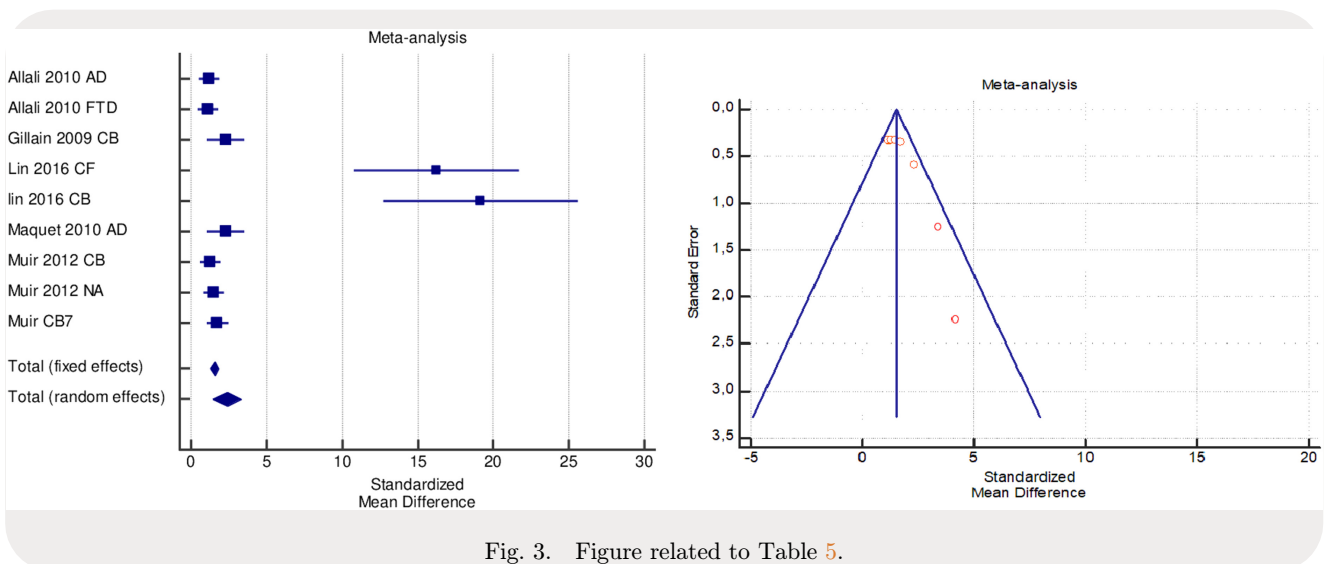


Fig. 3. Figure related to Table 5.

32% of patients with moderate and severe disease, respectively.^{28,33,34} Thus, gait assessment seems to be a useful tool for monitoring the progression of the disease with the aim of identifying and preventing postural instability.

Patients with dementia and mild cognitive impairment (the stage between the expected cognitive decline of normal aging and the more serious decline of dementia) walk more slowly and have more variability (CV) in their gait under single- and various dual-task conditions than patients without cognitive impairment.³⁵

Comparing studies: Gait parameters

We observed that the most studied parameter was gait speed, which was reported by nine papers^{4,5,12–18} and by five other papers during a dual-task activity.^{4,12–14,17} Cadence was recorded in only two papers^{4,18} and stride length was recorded in five studies for single-task conditions,^{4,5,12,13,18} whereas three reported it for dual-task conditions.^{4,12,13} Both the parameters are important because modifications of speed are physiologically due to an increase or decrease of cadence or stride length. Therefore, based on the obtained data, we can say that speed is the main abnormal gait parameter of patients with dementia. Among all gait parameters, for the relation between speed and executive function, speed could be a very important marker of the extent of involvement of motor areas of the brain in diffuse brain disease.³⁶ Gait speed is a holistic parameter that includes all others. Moreover, when speed is increased, it means that the locomotor system is at its maximal efficiency. Usual gait speed is associated with executive function, but maximum speed is more closely associated with cognition than usual speed. In this regard, Perry *et al.*³⁶ showed that there is a statistical correlation between gait velocity and the clinical condition of people with stroke. They showed that more affected hemiplegic patients walked significantly slower (< 0.4 m/s) than those who were affected (> 0.8 m/s). Similar findings can be found for people with Parkinson's disease³⁷ and multiple sclerosis.³⁸ The studies that investigated the association between gait speed and cognition only used the participants' usual gait speed and did not carry out a direct comparison of different gait speeds. It could be interesting to compare the severity of dementia with the degree of difficulty when walking faster. We propose

following the changes in speed in people with dementia as an objective indicator of disease progress. Our meta-analysis highlighted how slow gait and subjective cognitive decline are part of a motoric cognitive risk syndrome, with a high-risk status for the development and the worsening of dementia.

Gait parameters showed an association with various cognitive domains.^{5,18} Allali *et al.*⁵ concluded that higher stance time CV appears as a motor phenotype of cognitive decline. Verghese *et al.*¹⁸ reported that swing time could predict decline in the memory domain, whereas stride length could predict decline in the executive domain. They highlighted that gait parameters can predict cognitive decline and dementia, independently from cognitive performance.¹⁸

Correlation between gait parameters and types of dementia

According to De Cock *et al.*,³⁹ the balance and gait quality change differently between distinct types of dementia. The different types of dementia showed similar gait characteristics to those of Alzheimer's disease.^{5,17,18} Patients with Alzheimer's dementia were characterized by significant differences in stride time and stride width variability with respect to adults without neurological impairment or dementia.^{16,40}

In patients with frontotemporal dementia, worse motor performance was evident during walking in single-task conditions, in contrast to patients with Alzheimer's disease who showed only slight gait impairment in the same conditions. In frontotemporal dementia, gait was significantly slower, as suggested by the reduction of speed, stride length, and cadence with respect to patients with Alzheimer's disease. Among gait parameters, patients with frontotemporal dementia had higher stride time CV than patients with Alzheimer's disease and healthy controls during single and dual tasks. Stance time was modified in both cases of frontotemporal dementia and Alzheimer's disease, indicating a dynamic instability.¹⁷

Studies on spatiotemporal gait analysis in Lewy body dementia and Alzheimer's dementia showed that single-task walking changed similarly in both kinds of dementia in comparison with cognitively normal people. Velocity and stride length decreased, and double support (two feet simultaneously touching the floor) increased in both

groups of demented patients.⁴¹ The distinction between patients with Alzheimer's disease and those with subcortical lesions was related to gait speed.⁴²

Allali *et al.*⁵ examined the spatiotemporal gait parameters in mild and moderate dementia. They assessed a group with Alzheimer's dementia and another with non-Alzheimer's dementia.⁵ Patients with mild non-Alzheimer's dementia had significantly worse walking than patients with Alzheimer's disease in terms of stride length variability.⁵ Patients with moderate non-Alzheimer dementia presented significantly more disturbed gait parameters than patients with dementia in terms of walking speed, stride length, and stance time.⁵

Vergheze *et al.*¹⁸ included 12 patients with Alzheimer's disease, 17 with vascular dementia, and 4 with other kinds of dementias that were not specified. None of the gait parameters predicted a specific kind of dementia, and only the pace factor predicted the risk of vascular dementia.¹⁸

De Cock *et al.*³⁹ proposed that a decrease of step width could differentiate Alzheimer and frontotemporal dementia from vascular dementia and Lewy body dementia, in the mild dementia stage, according to the Clinical Dementia Rating.

Comparing studies: Single- and dual-task conditions

A few studies described the modifications in gait function during single- and dual-task conditions in patients with Alzheimer's disease^{4,5} and different types of dementia such as vascular dementia⁵ with respect to healthy controls or people with mild cognitive impairment.¹²⁻¹⁴ Dual-task conditions were examined in five papers and the type of dual task was different.^{4,12-14,17} In three articles, gait analysis was performed while the subjects walked counting backwards.^{5,12,13} For the dual-task conditions, other articles used counting backwards by ones, counting forward,⁴ counting backwards by one, naming animals, and counting backwards by sevens.¹⁴ Allali *et al.*⁵ reported that counting backwards by 3 digits, as the second task during gait performance, revealed more marked modifications in gait parameters than counting forward by 3 digits in elderly people with mild dementia compared with elderly people without dementia. Muir *et al.*¹⁴ revealed a significant increase of stance time CV with larger effects for backwards counting compared with naming animals. Another

article additionally found a significant increase in counting forward by one and counting backward.¹²

Correlation between gait parameters and types of dementia in dual-task activity

Montero-Odasso *et al.*⁴³ and Terney *et al.*⁴⁴ showed that the gait performance varied and became worse based on the kind of cognitive dual task used. A working memory test such as the counting-backwards task was more related to frontal lobe dysfunction and to cortical gait modifications in cases of early cognitive decline.⁴³ A test of semantic verbal fluency and memory, such as the animal-reciting task, was related to temporal lobe dysfunction. Patients with Alzheimer's disease performed better than vascular-dementia patients in verbal fluency.⁴⁴

Implications in rehabilitation

Maintaining the function of gait, decreasing the severity of dementia, and decreasing the risk of falls are the principal objectives of rehabilitation. Preserving the walking status and the correct postural balance in patients with dementia could improve the cognitive function.^{45,46} In order to slow down the course of dementia, a rehabilitation project with dual-task activities could be the key to therapeutic success.

Limitations

A lack of uniformity among the study designs (measured parameters, electronic instruments) may have affected the validity of the statistical analysis. Each study assessed different parameters, so that the results of meta-analysis were more accurate for parameters that were more frequently reported (e.g. gait speed). Another limitation is the absence of information about some clinical characteristics that could influence gait parameters, such as comorbidities affecting gait (osteoarthritis, arthrosis, or peripheral neuropathy), the use of drugs, and the presence of prostheses. Furthermore, in some studies, the sample was too small. Several studies did not evaluate the educational status of the participants, which could be a confounding factor and could influence the results.

The articles about dual tasks used different cognitive tasks, thus making the sensitivity of different modalities unclear.

Conclusions

Our systematic review identified the most sensitive parameters related to the different kinds of dementia, assessed by gait analysis. Pooling data within this meta-analysis revealed that several gait spatiotemporal parameters of gait discriminated best between dementia and healthy controls, including speed, cadence, stride time, stride time variability, stance time, stride length during single task and speed, stride time variability, and stride length in dual task.

The temporal parameters could predict the risk of falls more than spatial parameters, such as cadence, stride time, stride time variability, and stance time. They could be markers of full-blown dementia and predictors of functional dependence and risk of falling, especially during dual-task conditions.

Thus, gait analysis could contribute to the diagnosis and prognosis of dementia. The results could be used for the development of preventive interventions to reduce the burden of dementia, as well as specific rehabilitation interventions to better control postural instability and reduce the risk of falls.

Conflict of Interest

The authors have no conflicts of interest relevant to this article.

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