Title: Gait Parameters and Characteristics Associated with Increased Risk of Falls in People with Dementia: A Systematic Review

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ABSTRACT

Background: People with dementia fall twice as often and have more serious fall-related injuries than healthy older adults. While gait impairment as a generic term is understood as a fall risk factor in this population, a clear elaboration of the specific components of gait that are associated with falls risk is needed for knowledge translation to clinical practice and the development of fall prevention strategies for people with dementia.

Objective: To review gait parameters and characteristics associated with falls in people with dementia.

Methods: Electronic databases CINAHL, EMBASE, MedLine, PsycINFO, and PubMed were searched (from inception to April 2017) to identify prospective cohort studies evaluating the association between gait and falls in people with dementia.

Results: Increased double support time variability, use of mobility aids, walking outdoors, higher scores on the Unified Parkinson's Disease Rating Scale, and lower average walking bouts were associated with elevated risk of any fall. Increased double support time and step length variability were associated with recurrent falls. The reviewed articles do not support using the Performance Oriented Mobility Assessment and the Timed Up-and-Go tests to predict any fall in this population. There is limited research on the use of dual-task gait assessments for predicting falls in people with dementia.

Conclusion: This systematic review shows the specific spatiotemporal gait parameters and features that are associated with falls in people with dementia. Future research is recommended to focus on developing specialized treatment methods for these specific gait impairments in this patient population.

Keywords: Systematic review; Dementia; Gait; Mobility; Accidental falls; Risk assessment

Among chronic diseases in older adults, dementia is known to be the largest single contributor to disability and need for care (Wimo and Prince, 2010). In 2016 there were 47 million people with dementia worldwide and this number is projected to increase to 131 million by 2050 (Prince *et al*., 2016). The worldwide economic impact of dementia is also enormous, approximately $820 billion (USD) (Prince *et al*., 2016). One significant health problem in people with dementia is that they fall twice as often as cognitively intact older adults (Tinetti, *et al*., 1988; Montero-Odasso, *et al*., 2012). Following a fall, people with dementia incur more serious and major fall-related injuries such as hip fractures and have worse treatment outcomes (Magaziner *et al.*, 1990; Inoue *et al.*, 2000; Kallin *et al.*, 2005; Vidan *et al.*, 2005; Moyle *et al.*, 2007). The increasing number of people with dementia, the associated high economic cost, and the suffering caused by falls make finding preventative and rehabilitative measures for falls in this population a top research priority.

Several fall prevention programs have been developed for the general older adult population (Hill-Westmoreland, *et al*., 2002; Scott *et al.*, 2007; Pfortmueller, *et al*., 2014; Phelan *et al.*, 2015). However, they are not necessarily effective in people with dementia (Shaw *et al.*, 2003). An approach to remedy this shortcoming is to first thoroughly understand the most significant fall risk factors in this population. One of the most consistent fall risk factors in people with dementia is mobility and gait impairment (Buchner and Larson, 1987; Nakamura *et al*., 1996; Horikawa *et al.*, 2005; S.W. *et al.*, 2012; Kearney *et al.*, 2013; Suttanon *et al.*, 2013; Doi *et al.*, 2015). Gait is a complex task that can be measured and quantified in several ways and therefore “gait impairment” is not informative for what aspects of gait are, or are not, associated with an increased fall risk. With an understanding that people with dementia suffer from impaired gait, which leads to an increased risk of falling, one factor that requires more attention is the particular components of gait that contribute to the increased risk of falls in this population. To discover effective gait rehabilitation and fall prevention strategies, it is necessary to fully understand and describe gait and its association with falls in people with dementia.

Gait relies on a simultaneous interaction of the motor system, sensory control, and cognitive functions (Jahn, *et al*., 2010). For instance, impaired gait parameters, such as short steps and long double support times are associated with smaller sensorimotor and frontoparietal regions within the motor, visuospatial, and cognitive processing domains (Rosano *et al.*, 2008). Further, the negative effects of cognitive impairment on gait are supported by several studies, demonstrating the importance of intact cognition in walking (Ble *et al.*, 2005; Hausdorff *et al.*, 2005; Merory *et al.*, 2007; Allali *et al.*, 2008; Nadkarni *et al.*, 2009). For instance, deterioration in cognitive function leads to a slow gait speed (Watson *et al.*, 2010) and people with dementia compared to healthy older adults display more variability in stride length (Nakamura *et al*., 1996). A systematic review of quantitative gait analysis in people with dementia demonstrated that gait becomes more impaired with progressing severity of dementia (van Iersel *et al.*, 2004). These findings reveal that gait is more than just an automatic behavior: rather gait requires attention and input from multiple structures within the central nervous system.

Previous systematic reviews have certainly emphasized the importance of impaired gait as a falls risk factor (Harlein *et al.*, 2009; Kropelin *et al.*, 2013; Fernando *et al.*, 2017), however, to the authors' knowledge, no systematic review has summarized the specifics and details of this factor in the estimation of risk for people with dementia. This type of review is necessary in order to give meaning to the concept of gait impairment as a fall risk factor in people with dementia and, knowledge translation to the clinical practice of what is relevant to assess and to develop and evaluate fall prevention strategies directed at the specific deficits. In light of the lack of efficacy of interventions to rehabilitate gait and prevent falls in people with dementia, it is also important to take a step back and investigate how the boundaries of current knowledge can be expanded in regard to gait impairment and falls in this population.

Objectives

1) Conduct a systematic review of the existing literature and identify prospective studies that investigated gait as a fall risk factor in people with dementia;

2) Clarify and summarize spatiotemporal gait parameters and other gait characteristics associated with falls in people with dementia;

3) Report psychometric properties of gait assessment tests used for people with dementia to predict falls;

4) Stratify prospective studies that have investigated gait as a fall risk factor in people with dementia based on their type of dwelling – institutional or community.

Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline and checklist were used to plan, develop, and report the results of this study (Moher *et al.*, 2010). This systematic review was guided by an *a priori* published protocol on PROSPERO, registration number: CRD42017059936.

Data sources and searches

To identify articles, a detailed systematic search of the existing literature without date limitation was conducted between March 30, 2017, and April 13, 2017. Electronic databases CINAHL, EMBASE, MedLine, PsycINFO, and PubMed were searched. The Medical Subject Headings and keywords used to search the databases are shown in Table 1. The reference lists of extracted review articles and relevant articles with a focus on gait and fall risk in people with dementia were manually searched to identify articles that were not captured in the electronic database searches.

Study selection

The following inclusion criteria were used to select the studies for this systematic review:

1) Prospective cohort studies;

2) Studies that consisted of samples with 100% of participants having confirmed diagnosis of dementia or mild cognitive impairment (MCI) or included a sub-group analysis for the people with dementia or MCI;

3) Studies that investigated gait as a risk factor for falls;

4) Studies that explicitly detailed the gait assessment protocol;

5) Studies that reported falls as an outcome measure;

6) Studies with explicit inclusion and exclusion criteria and demographic information;

7) Studies that reported adjusted risk estimates or diagnostic test properties.

No restriction was set by the severity of dementia, type of setting, age of participants, follow-up time frames, and the type of fall evaluated.

The article selection process was done independently by two reviewers (SM and AD) in five stages. In the first stage, the electronic database searches were conducted and reference lists of relevant articles with a focus on gait and falls in people with dementia were manually searched. In the second stage, duplicates were removed. In order to minimize the number of false positives and false negatives, two different software systems were used to remove duplicates: Mendeley (version 1.17.10) and EndNote (version 7.7.1). In the third step, titles were screened. For a title to be accepted, it needed to have one term out of the dementia group of key terms and at least one term from either the gait or the falls group of key terms. The fourth stage consisted of screening the abstracts against the inclusion criteria. Articles that met the inclusion criteria were then selected to have their full text reviewed at stage five. Disagreement at each stage was resolved by consensus. Conference proceedings, books, dissertations, and unpublished data were not included in this systematic review.

Quality assessment

A quality of reporting assessment was performed independently by two reviewers (SM and AD). The 33-item scale by Tooth and colleagues (Tooth *et al.*, 2005) was used. This scale is a reliable and validated tool for determining threats to internal and external validity in observational studies. The checklist contains questions about the study population and sample, sample size and power, consent, follow-up, method of data collection, biases, missing data, data analysis, confounders, effect sizes, as well as relatability to target population and generalizability. The maximum score is 33, with a higher score indicating greater reporting quality. The inter-rater reliability of the quality of reporting evaluation was assessed with intraclass correlation coefficient (ICC) (Phillips *et al*., 2001) using the Statistical Package for the Social Sciences (version 24.0) program (SPSS, Inc, Chicago, Illinois). The result of the reliability analysis showed an ICC value of 0.94 (95% CI: 0.83 to 0.98), which corresponds to an excellent inter-rater reliability (Portney and Watkins, 2001).

Data extraction

The following information was extracted from the articles included in the study by SM: authors, date of publication, country, setting, type of dementia, method for diagnosing or confirming dementia, inclusion and exclusion criteria, sample size (% female), mean age, follow-up duration, type of fall evaluated, method of fall ascertainment, percentage of participants that fell during the study, gait assessment protocols, results of gait and falls assessments, adjusted risk estimates for future falls, and reported psychometric properties of diagnostic tests. We performed a careful comparison of the gait assessment measurements and the corresponding reported results of each article to check for missing outcomes (Moher *et al.*, 2010). For instance, if a study collected gait data using the Unified Parkinson's Disease Rating Scale (UPDRS), it is expected that the results of this assessment to be reported in the results section; if not, it will be considered as a missing outcome.

Data synthesis and analysis

It was planned *a priori* that a fixed-effects model meta-analysis of gait outcomes would be conducted using adjusted risk estimate data. However, due to an observed heterogeneity across studies in methods of gait assessment, duration of studies, type of dementia, statistical analysis, and data presentation, the statistical pooling of results was deemed not appropriate. Therefore, a meta-analysis of results was not conducted, and a descriptive summary was undertaken.

Results

Out of a total of 1847 retrieved articles, 165 abstracts including 11 non-English articles were screened. Abstracts of the non-English articles were also provided in English and none of these studies met the inclusion criteria. In total, 33 articles were selected for full-text review. Twenty-three articles did not meet the inclusion criteria; their full citation and the reasons for exclusion are summarized in Appendix A1. See Appendix A1 published as supplementary material online attached to the electronic version of this paper at https://www.cambridge.org/core/journals/international-psychogeriatrics. Ten articles met the inclusion criteria (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Allan *et al.*, 2009; Pellfolk *et al.*, 2009; Sterke *et al.*, 2010, 2012, Taylor *et al.*, 2012, 2014; Schwenk *et al.*, 2014; Gietzelt *et al.*, 2014). Figure 1 shows a flow diagram of the article selection process. One study failed to report an ethics approval statement (Camicioli and Licis, 2004).

The studies in this review represent 1026 older adults with dementia. Sample sizes ranged from 40 (Gietzelt *et al.*, 2014) to 174 (Taylor *et al.*, 2014). Gender composition was more skewed towards females in seven of the 10 studies (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Pellfolk *et al.*, 2009; Sterke *et al.*, 2012; Taylor *et al.*, 2012, 2014), with the highest number of female participation at 86% (Camicioli and Licis, 2004). One study did not report the gender composition (Sterke *et al.*, 2012). The mean age range of participants was 76 (+/-8.3) (Gietzelt *et al.*, 2014) to 83 (+/-9.57) years (Camicioli and Licis, 2004). See Table 2 for full study details.

Nine studies reported associations between gait findings and future falls with adjusted risk estimates (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Allan *et al.*, 2009; Pellfolk *et al.*, 2009; Sterke *et al.*, 2010, 2012, Taylor *et al.*, 2012, 2014; Schwenk *et al.*, 2014). In addition to risk estimates, three studies also determined the psychometric properties of tools used to quantify gait for future fall risk (Sterke *et al.*, 2010, 2012; Schwenk *et al.*, 2014). One study only determined the psychometric properties of the tools that were used to quantify gait for future falls (Gietzelt *et al.*, 2014). See Table 3 for full details.

In two studies, the method of diagnosis was not stated (Pellfolk *et al.*, 2009; Gietzelt *et al.*, 2014) and in two it was not clear whether all participants had a formal diagnosis by a specialist clinician (Taylor *et al.*, 2012, 2014). A variety of scales were used to ascertain the severity of dementia with the most common being the Mini-Mental State Examination (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Allan *et al.*, 2009; Taylor *et al.*, 2012, 2014; Gietzelt *et al.*, 2014). Other scales that were used include the Addenbrooke's Cognitive Examination-Revised score (Taylor *et al.*, 2012, 2014), the Global Deterioration Scale (Sterke *et al.*, 2010, 2012), the Clinical Dementia Rating (Camicioli and Licis, 2004), the Brief Cognitive Rating Scale (Camicioli and Licis, 2004), the Cumulative Illness Rating Scale (Camicioli and Licis, 2004), and the Gottfries-Gottfries Scale (Pellfolk *et al.*, 2009).

Nine studies reported the outcome of people who sustained any fall (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Allan *et al.*, 2009; Pellfolk *et al.*, 2009; Sterke *et al.*, 2010, 2012; Schwenk *et al.*, 2014; Gietzelt *et al.*, 2014; Taylor *et al.*, 2014) and one study focused on recurrent (≥2) fallers (Taylor *et al.*, 2012). There was no definition of falls in three studies (Sterke *et al.*, 2010, 2012; Gietzelt *et al.*, 2014). Aside from a few slight variations in phrasing, in seven studies the definition of a fall was an event that resulted in a person coming to rest unintentionally on the ground or other lower level (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Allan *et al.*, 2009; Pellfolk *et al.*, 2009; Taylor *et al.*, 2012, 2014; Schwenk *et al.*, 2014). Charts, nursing logs, and incidence registration forms were used in six studies (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Pellfolk *et al.*, 2009; Sterke *et al.*, 2010, 2012; Gietzelt *et al.*, 2014). In three studies, falls reported by patients and not witnessed by staff were not included (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Sterke *et al.*, 2010). This approach (excluding un-witnessed falls) was in contrast with another study where most of their reported falls (nearly 80%) were not witnessed (Pellfolk *et al.*, 2009). Fall calendars, diaries, and regular telephone prompts were used in four studies (Allan *et al.*, 2009; Taylor *et al.*, 2012, 2014; Schwenk *et al*., 2014).

Quality assessment results

The quality assessment showed that all of our studies had moderate reporting quality. The quality scores of the reviewed articles ranged from 20 to 25 with a mean of 22.2 (+/-1.8). Prominent deficits in reporting included lack of justification for chosen sample sizes, providing reasons for non-consenting participants, a comparison of consenters and non-consenters, and addressing biases quantitatively.

Methods of gait assessment

Assessment of gait fell into six categories:

1) Functional performance using standardized clinical outcome measures including the Timed Up-and-Go (TUG) (Gietzelt *et al.*, 2014; Schwenk *et al*., 2014; Taylor *et al.*, 2014), and the Performance Oriented Mobility Assessment (POMA) test (Allan *et al.*, 2009; Sterke *et al.*, 2010; Gietzelt *et al.*, 2014; Schwenk *et al.*, 2014),

2) Spatiotemporal gait parameters (Camicioli and Licis, 2004; Sterke *et al.*, 2012; Taylor *et al.*, 2012, 2014; Gietzelt *et al.*, 2014),

3) An objective movement rating scale; the UPDRS (Camicioli and Licis, 2004; Allan *et al.*, 2009),

4) Evaluation for use of mobility aids (Eriksson *et al*., 2008; Allan *et al.*, 2009; Pellfolk *et al.*, 2009; Taylor *et al.*, 2012, 2014)

5) Monitoring of outdoor walks (Pellfolk *et al.*, 2009; Taylor *et al.*, 2014),

6) Amount of walking activity through using

a) Questionnaires with the assistance of caregivers (Taylor *et al.*, 2014), and

b) Accelerometers to examine walking patterns for 24 hours (Schwenk *et al.*, 2014), and one week (Gietzelt *et al.*, 2014).

Spatiotemporal gait parameters investigated were: velocity (Camicioli and Licis, 2004; Sterke *et al.*, 2012; Taylor *et al.*, 2012, 2014; Gietzelt *et al.*, 2014), cadence (Camicioli and Licis, 2004; Sterke *et al.*, 2012; Taylor *et al.*, 2012), stride time (Sterke *et al.*, 2012), double support time (DST) (Sterke *et al.*, 2012; Taylor *et al.*, 2012), stride length (Camicioli and Licis, 2004; Sterke *et al.*, 2012; Taylor *et al.*, 2012), base of support (Camicioli and Licis, 2004; Sterke *et al.*, 2012), stride length variability (Camicioli and Licis, 2004; Sterke *et al.*, 2012), step length variability (Taylor *et al.*, 2012), DST variability (Sterke *et al.*, 2012), stride time variability (Sterke *et al.*, 2012), and base of support variability (Camicioli and Licis, 2004; Sterke *et al.*, 2012). The GAITRite® system was used to obtain spatiotemporal gait parameters in three studies, wherein all of the participants were asked to walk at their preferred speed (Camicioli and Licis, 2004; Sterke *et al.*, 2012; Taylor *et al.*, 2012). In one study, these measurements were acquired under three testing conditions: 1) without tester input; 2) with verbal persuasion; and 3) with physical cue (Sterke *et al.*, 2012). Gait measurements were also assessed using dual-task testing in one study (Camicioli and Licis, 2004). In this study, a cognitive dual-task of counting from one upward by ones was used as the participants walked for the length of the GAITRite® mat. One study quantified walking activity parameters related to gait using accelerometers in four categories: 1) percentage of walking in 24-hour, 2) walking bout average duration, 3) longest walking bout duration, and 4) walking bout duration variability (Schwenk *et al.*, 2014).

Psychometric properties of gait assessment tests

One study reported the psychometric properties of the POMA test (Sterke *et al.*, 2010). The best values for predicting falls in the POMA-Total (POMA-T) and the POMA-Gait subtype (POMA-G) were a score of ≤ 21 and a score of ≤ 9 respectively, with the POMA-T having a better predictive validity. According to these results, people with dementia who score lower than these values are at an increased risk of falls within a 3-month period.

Cutoff values for spatiotemporal gait parameters measured using the GAITRite® system for prediction of a fall were determined for velocity, stride length, base of support variability, and double support time (DST) variability (Sterke *et al.*, 2012). Based on the psychometric properties of these parameters, reduced velocity, and reduced mean stride length were the best predictors of any fall.

Using accelerometers to monitor walking activity, a cutoff of 15 seconds for 'walking bout average duration' (i.e., average duration of all walking bouts conducted during the 24-hour measurement), gave 93% sensitivity, but low specificity (33%), and a cutoff of eight seconds gave 93% specificity but low sensitivity (14.3%) (Schwenk *et al.*, 2014). However, when a cutoff of 15 seconds for ‘walking bout average duration’ was combined with ‘previous faller’ status, high diagnostic accuracy was obtained (Schwenk *et al.*, 2014). This combination of outcomes significantly improved fall prediction (Schwenk *et al.*, 2014). Another study also used accelerometers for fall prognosis and reported that with a 4-month follow-up period it is possible to classify gait episodes in being associated with a faller or a non-faller with an accuracy of 75% (Gietzelt *et al.*, 2014). Psychometric properties of the other types of gait assessment tools were not assessed.

Gait and falls association

Increased DST variability (Sterke *et al.*, 2012), higher scores on the UPDRS (Camicioli and Licis, 2004), participation in outdoor walks (Pellfolk *et al.*, 2009), use of mobility aids (Eriksson *et al*., 2008; Pellfolk *et al.*, 2009), and lower average walking bouts in 24 hours (Schwenk *et al.*, 2014) were significant predictors of any fall. Increased DST and step length variability were associated with recurrent falls (Taylor *et al.*, 2012). There were conflicting reports regarding other spatiotemporal gait parameters associated with any fall. Slow gait speed, reduced stride length, and decreased base of support variability were shown to be predictors of any fall in one study (Sterke *et al.*, 2012), but not in another study that measured these parameters (Camicioli and Licis, 2004). Conversely, low cadence was found to be a predictor of any fall in one study (Camicioli and Licis, 2004), and not in the other study that measured it (Sterke *et al.*, 2012).

All the studies in this review that used and reported the results of TUG and POMA did not recommend the use of these tests to predict falls in people with dementia (Allan *et al*., 2009; Sterke *et al*., 2010; Schwenk *et al*., 2014; Gietzelt *et al*., 2014). Specifically, performance on the

POMA test was not a predictor of any fall in two studies (Schwenk *et al*., 2014; Allan *et al*., 2009). Only one study reported that performance on the POMA-T was a significant predictor of any fall (Sterke *et al*., 2010). Performance on the POMA-G (Sterke *et al*., 2010) and TUG (Gietzelt *et al*., 2014; Schwenk *et al*., 2014) was also not predictive of any fall.

Gait assessments while carrying out a secondary cognitive task during walking did not provide any additional benefits in predicting any fall compared to the single task of walking (Camicioli and Licis, 2004). The amount of overall walking activity was also not associated with any fall (Schwenk *et al*., 2014; Taylor *et al*., 2014). See Table 4 for a summary.

Community-dwelling (CD) versus institutional-dwelling (ID)

In total, two studies recruited CD participants (Taylor *et al*., 2012; Schwenk *et al*., 2014), six studies recruited ID participants (Camicioli and Licis, 2004; Eriksson *et al*., 2008; Pellfolk *et al.*, 2009; Sterke *et al.*, 2010, 2012; Gietzelt *et al.*, 2014; Schwenk *et al.*, 2014), and two studies had a mixture of both (Allan *et al*., 2009; Taylor *et al*., 2014). Among CD participants: the only significant predictor of any fall was lower average walking bouts in 24 hours (Schwenk *et al*., 2014). Spatiotemporal gait parameters were evaluated in CD participants to predict recurrent falls, and increased DST and step length variability were found to be significant predictors (Taylor *et al*., 2012). Unfortunately, spatiotemporal gait parameters, mobility aid use, and participation in outdoor walks were not investigated in CD people to predict any fall. Among the ID participants: increased DST variability (Sterke *et al*., 2012), poor performance on the POMA-T (Sterke *et al*., 2010), higher scores on the UPDRS (Camicioli and Licis, 2004), walking with mobility aids (Eriksson *et al*., 2008; Pellfolk *et al*., 2009), and participation in outdoor walks (Pellfolk *et al*., 2009) were significant predictors of any fall. Recurrent falls were not investigated in ID participants. The two studies that used a mixture of both CD and ID participants did not report significant gait results (Allan *et al*., 2009; Taylor *et al*., 2014).

Missing outcomes

Four studies in this review failed to report all their outcomes. One study did not report all results regarding their gait measurements (Gietzelt *et al*., 2014), one study did not report complete results regarding their dual-task gait assessments (Camicioli and Licis, 2004), and one study did not report their UPDRS and the mobility aid usage results (Allan *et al*., 2009). Three studies did not report adjusted risk estimates for non-significant results (Camicioli and Licis, 2004; Allan *et al*., 2009; Schwenk *et al*., 2014). In addition, one study did not include all their measured gait variables in a multivariate regression analysis to determine their significance as predictors of falls, despite them being significant in the univariate analysis (Taylor *et al*., 2014). The authors explain this choice by stating that this was done in order to avoid a violation of assumptions concerning the number of predictor variables as compared to the sample size. However, these variables could be included in separate multivariate regression models or the sensitivity analysis could have been reported.

Discussion

This systematic review demonstrated that increased DST variability (Sterke *et al*., 2012), outdoor walking (Pellfolk *et al*., 2009), higher scores on the UPDRS (Camicioli and Licis, 2004), and use of mobility aids (Eriksson *et al*., 2008; Pellfolk *et al*., 2009) were significant risk factors for any fall in CD people with dementia. Lower average walking bouts during a 24-hour period was the only significant predictor of any fall among ID people with dementia (Schwenk *et al*., 2014), and increased DST and step length variability were significant predictors of recurrent falls in this population (Taylor *et al*., 2012). Conflicting evidence exists regarding other gait parameters and prognostic tests to predict falls.

The POMA test has a good inter-rater reliability (ICC=0.97 for POMA-T, and ICC=0.88 for POMA-G), test-retest reliability (ICC=0.96) (van Iersel *et al*., 2007) and prognostic validity (Sterke *et al*., 2010) for future falls (reported above) in people with dementia. However, performance on this test strongly depends on how well the participants understand and follow instructions (Sterke *et al*., 2010). One study reported that 41% of the participants had difficulty following one or more of the instructions (Sterke *et al*., 2010). Consequently, a participant may receive a score of zero on a component of this test not because of gait issues but due to cognitive impairment (Sterke *et al*., 2010). This leads to constant but low gait performance, resulting in high reliability values but inadequate measurements of gait (van Iersel *et al*., 2007). Therefore, although the POMA test shows high reliability (van Iersel *et al*., 2007) and validity to predict falls in people with dementia (Sterke *et al*., 2010), we do not recommend it for two reasons: 1) other studies report that this test is not predictive of falls (Allan *et al*., 2009; Gietzelt *et al*., 2014; Schwenk *et al*., 2014) and 2) the test results being tainted by the participants' cognitive deficiencies (Sterke *et al*., 2010; Schwenk *et al*., 2014).

The TUG test results were not predictive of any fall for people with dementia (Gietzelt *et a*l., 2014; Schwenk *et al*., 2014), which is consistent with the existing literature in cognitively healthy older adults (Beauchet *et al.*, 2011). However, there are two additional points that have not escaped our notice: although the TUG test has shown to have good inter- and intra-rater reliability (with a range of ICC values from 0.75 to 0.94) for people with dementia (Fox *et al.*, 2016), research has shown that participants sometimes need prompts or reminders to continue the task (Taylor *et al.*, 2013). A recent systematic review reported that most studies used a modified version of the TUG (e.g., integrating the use of prompts), which may lead to the validity of the test to be undermined by deviations from the standard protocol (Fox *et al.*, 2016). In addition, there is a discrepancy in the current literature regarding the feasibility of this test in people with moderate to severe dementia, with one study supporting its use (Ries *et al.*, 2009), and another arguing that it is, in fact, impractical in people with severe dementia (Tappen *et al.*, 1997). In spite of this reported discrepancy, one of the studies in this review utilized TUG for people with severe to most severe dementia (Gietzelt *et al*., 2014). Keeping in mind that this test is not predictive of falls in cognitively healthy older adults, it seems impractical to use it in people with dementia where the validity of the test can be undermined by participants not being able to follow the instructions. Future research is recommended to use appropriate tools for the population of interest and to consider whether participants can complete the test according to standard protocol (Fox *et al.*, 2016).

There was a lack of consistency in spatiotemporal gait parameters that were uniformly associated with an increased fall risk. Increased DST variability was found to be the only gait parameter associated with falls, however, this spatiotemporal parameter was only evaluated in one study (Sterke *et al*., 2012), and this is susceptible to individual study effects. For instance, this study used physical cueing and verbal persuasion during their gait assessments, and the type and amount of added physical cues and verbal persuasion were not reported and may have varied across participants. The other studies that evaluated spatiotemporal gait parameters did not state whether they used any cues. This significant difference in methodology, as well as differences in exclusion criteria, duration of follow-up, type of dementia, and statistical analysis techniques, could account for the differences seen between the results of studies that investigated spatiotemporal gait parameters.

The use of a mobility aid was a significant predictor of any fall in the two studies that investigated and reported this factor (Eriksson *et al*., 2008; Pellfolk *et al*., 2009), which is consistent with existing literature in healthy older adults (Deandrea *et al.*, 2010). This fall risk factor may seem unexpected because a mobility aid is prescribed to assist walking (Bateni and Maki, 2005; Pellfolk *et al.*, 2009). Research on mobility aid use in people with mild to moderate

AD has shown that ambulation using mobility aids increases the cognitive load and requires greater attentional costs (Muir-Hunter and Montero-Odasso, 2017). Another potential mechanism regarding the increased risk of falls and mobility aids is that mobility aids interfere with lateral movement of the feet and inhibit compensatory stepping reactions during the lateral loss of balance (Bateni *et al.*, 2004). Since slowing in simple reaction time and choice reaction time is a feature of dementia (Pate and Margolin, 1994; Baddeley *et al.*, 2001; Levinoff *et al*., 2005), compensatory reactions may be further hampered in this population. Although the use of mobility aids has been shown to be associated with increased risk of falls in studies of this review, the specific problems encountered by subjects have not be identified.

Walking outdoors was associated with any fall (Pellfolk *et al*., 2009), however, details of the outdoor conditions were not reported. This information can be crucial as different outdoor environments may have variable impacts on the risk of falling. Circumstances of outdoor falls in cognitively healthy older adults (mixture of CD and ID) have been examined, and the results indicate that outdoor falls mostly occurred on snowy grounds and participants often described their falls involving unsuitable footwear and/or trips on uneven paths, tree roots or curbsides which were either misjudged or not visible (Leavy *et al.*, 2015). However, these findings cannot be extrapolated for people with dementia, as this is a distinct population with unique characteristics and a higher risk for falls (Tinetti *et al*., 1988). Recognizing specific circumstances of falls during outdoor walks can potentially improve the predictive power of this fall risk factor and can allow for appropriately focused prevention measures.

Unlike the general population of older adults (Muir-Hunter and Wittwer, 2016), in people with dementia, dual-task gait testing does not add any benefits to the predictive power of gait assessment for future falls compared with gait assessment using the single task of walking (Camicioli and Licis, 2004). However, the secondary task chosen by the researchers in this study was relatively simple, and those authors rationalize their choice by stating that their participants could not perform more difficult secondary tasks (Camicioli and Licis, 2004). This information is incomplete because it is ambiguous whether participants made errors in performing the more difficult secondary cognitive task or stopped walking altogether (i.e., the performance of both tasks deteriorated), and it is unclear how participants' threshold for performing the task was calculated. Being unable to correctly perform a secondary cognitive task does not invalidate its use in dual-task assessments, as performing an additional task is meant to increase the cognitive and attentional load which can lead to a trade-off between accuracy and gait performance (McIsaac *et al*., 2015). It is imperative to investigate and report participants' abilities to perform the secondary task as a single assignment in isolation prior to introducing it as a dual-task (Plummer *et al.*, 2013). This first essential step and detailed information about the nature of the more difficult secondary task were not reported in this study, and therefore the conclusions drawn from it should be interpreted with caution.

Directions for future research

The associations of the identified gait characteristics with an increased risk of falls are based on the reported adjusted risk estimates. Both protective and risk factors were identified in this review. Different studies, depending on the designs, used different measures to report the effect sizes, such as odds ratio (OR), relative risk, hazard ratio, and incidence risk ratio (IRR). Measures of association ranged from an OR of 0.79 for 'walking bout average duration' (Schwenk et al., 2014), an indication of a protective effect, to an IRR of 5.16 for the 'use of mobility aids' (Eriksson et al., 2008), which can be considered a notable risk factor. These measures indicate that there are associations between the gait parameters and risk of falls, but the determination of use of these values in a clinical setting will have to be assessed with evaluation of the psychometric properties of these parameters as diagnostic tests. Furthermore, whether these factors are modifiable with intervention is another aspect of clinical relevance that still needs to be determined.

In addition, future research is recommended to investigate spatiotemporal gait parameters in CD people with dementia in order to predict falls in this specific population. All the articles had older adults as their study sample (>65 years) and none of them had participants with MCI or frontotemporal dementia. These particular patient populations may have unique gait impairments associated with falls; therefore, prospectively designed research is needed in younger people (<65 years) with dementia and in people with MCI and frontotemporal dementia to predict falls in these populations. The fourth issue that merits further research is regarding the utilization of dual-task gait assessment to predict falls in people with dementia, as currently there is limited research on the efficacy of this method. Fifth, more detail regarding the use of mobility aids as a fall risk factor is needed. For instance, it is essential to recognize whether participants were mostly using the devices to walk a straight path or in curved paths when the falls occurred as previous research has shown that compared with straight-path walking, curved-path walking involves different cognitive demands for gait (Lowry *et al.*, 2012). In addition, more information regarding the specific types of mobility aids (e.g.: single straight cane or quad cane) that are used by participants is needed. The sixth point that requires attention concerns the ‘walking outdoor’ fall risk factor as the word ‘outdoor’ is a non-specific term. For instance, walking on flat asphalt could potentially be different than walking in a garden, or walking in a quiet neighborhood versus a busy street. Risk of falling could also change due to weather. This information can be critical for clinicians and caregivers to reduce the risk of falling by taking appropriate precautions.

Strengths and limitations

One of the strengths of this study was adherence to a systematic protocol and selection of articles by two independent reviewers, thereby reducing the risk of bias in study selection and evaluation. Our inclusion criteria were broad, including MCI and all types of dementia, different settings, and no limitations by age or date of publication. We did not exclude non-English articles and screened these abstracts in stage four of our study selection process. The retrieved non-English articles did not meet our inclusion criteria. Our rigorous search strategy was conducted in five major electronic databases and we also manually searched the reference lists of included papers as well as relevant review papers with a focus on fall risk in people with dementia. Two reviewers evaluated the quality of reporting of the included articles independently and the inter-rater reliability of the evaluation was excellent. The main limitation of this systematic review rests in the limitations of the reviewed articles, including lack of reporting full results (significant and non-significant), full protocol details, and rationale for choosing a specific study design. These significant limitations within the literature can negatively impact knowledge translation into clinical practice. It should also be noted that having a large sample size in these types of studies can affect reaching statistical significance. However, in this systematic review we did not observe any relationship between sample sizes and the significance of gait parameters. For instance, two studies with distinctly different sample sizes report a similar effect (Pellfolk *et al*., 2009; Eriksson *et al*., 2008). Further, in the context of variable sample sizes, the precise way to determine whether a measure is truly related to the outcome of interest would be through conducting a meta-analysis. This would increase power to detect small effect sizes or those that were inconsistently reported by different studies. This is particularly of value since, except for one study (Taylor *et al*., 2012), no study that we reviewed had provided evidence for sample size calculation. However, as previously mentioned, a meta-analysis of the results was deemed not appropriate due to the observed heterogeneity of the methods and variables.

Conclusion

This systematic review identified increased DST variability, high scores on the UPDRS, outdoor walking, and use of mobility aids to be gait-associated predictors of any fall in ID, and lower average walking bouts to be the only gait-associated predictor of any fall in CD people with dementia. In addition, increased DST and step length variability were significant predictors of recurrent falls in ID people with dementia. Unfortunately, the literature provides contradicting results regarding other spatiotemporal gait parameters and cannot be used to provide recommendations. Despite established reliability, the reviewed articles do not support the use of the POMA and TUG tests to predict falls for people with dementia. The POMA test is not recommended due to contradicting results regarding its predictive ability for future falls and the feasibility of conducting this test in this population. The TUG test results did not show significance for predicting falls in this population. Further research is needed to understand specific circumstances preceding falls during outdoors walks and when patients use mobility aids. There is limited research on the prognostic validity of dual-task gait assessments in predicting falls for people with dementia. In addition, prospectively designed research for predicting falls is needed for people with MCI, frontotemporal dementia, and younger (65≥ years) patients with dementia. The identified spatiotemporal parameters and characteristics in this review can be used in future studies to develop and evaluate gait rehabilitation techniques and fall prevention strategies directed at these specific deficits and features.

Supplementary material:

Appendix A1 is a Table consisting of articles that their full-text was reviewed but they were not included in the systematic review because they did not meet the inclusion criteria. The reasons for exclusion of each article is also listed in this Table.

Conflict of Interest

None

Description of Authors' roles

Each of the authors has read and concurs with the content in the final manuscript. S. Modarresi developed the inclusion criteria and search key terms, performed the search, performed the quality appraisal, extracted study characteristics, and drafted the manuscript. A. Divine, replicated the search, performed the quality appraisal, and revised the manuscript. J. Grahn supported the development of the study and revised the manuscript. T. J. Overend supported the development of the study and revised the manuscript. S. W. Hunter supervised the development of the study including the inclusion criteria and the writing process and revised the manuscript.

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Figure/Table legend/caption

Figure 1: *caption:* Flow diagram of literature search.

Table 1: *caption:* Medical Subject Headings and keywords that were used to search the databases.

Table 2: *caption:* Summary of study details for papers included in systematic review (n=10). *Legend:* %F, percentage of sample that were females; ACE-R, Addenbrooke's cognitive examination – revised; AD, Alzheimer's disease; CD, community dwelling; CI, cognitive impairment; CNS, central nervous system; DLB, dementia with Lewy Bodies; DM, diabetes; h, hour; m, meter; MMSE, mini mental state examination; n/r, not reported; PDD, Parkinson's disease dementia; SD, standard deviation; TIA, transient ischemic attack; TUG, timed up and go; VD, vascular dementia. *, Quality of reporting assessment was performed using the 33-item scale by Tooth and colleagues. The maximum score is 33, with a higher score indicating greater reporting quality.

Table 3: *caption:* Summary of significant and non-significant gait and falls associations, adjusted risk estimates, and psychometric properties of tools used to quantify gait for future fall risk. *Legend*: BOS, base of support; CI, confidence interval; cm, centimeter; DST, double support time; HR, hazard ratio; IRR, incident rate ratio; MT, moderate time; NPV, negative predictive value; n/r, not reported; OR, odds ratio; POMA, performance oriented mobility assessment; POMA-G, POMA-Gait; POMA-T, POMA-total; PPV, positive predictive value; s, second; TUG, timed up and go; UPDRS, Unified Parkinson's Disease Rating Scale. Shaded areas indicate that those assessments were not an objective of the study. The bolded entries in the third column indicate statistical significance.

Table 4: *caption*: Summary of evaluated gait measures and findings.

Legend: Vlc, velocity; Cdnc, cadence; BOS, base of support; DST, double support time; SL, stride length; ST, stride time; STL, step length; /v, variability; POMA, Performance Oriented Mobility Assessment; TUG, Timed Up and Go; MA, mobility aid; UPDRS, Unified Parkinson's Disease Rating Scale; WA, walking activity; (p), specific walking pattern; ODW, outdoor walking; n/r, not reported; n/s, not significant; s, significant. Shaded areas indicate that those assessments were not an objective of the study.

Figure 1. Flow diagram of literature search.

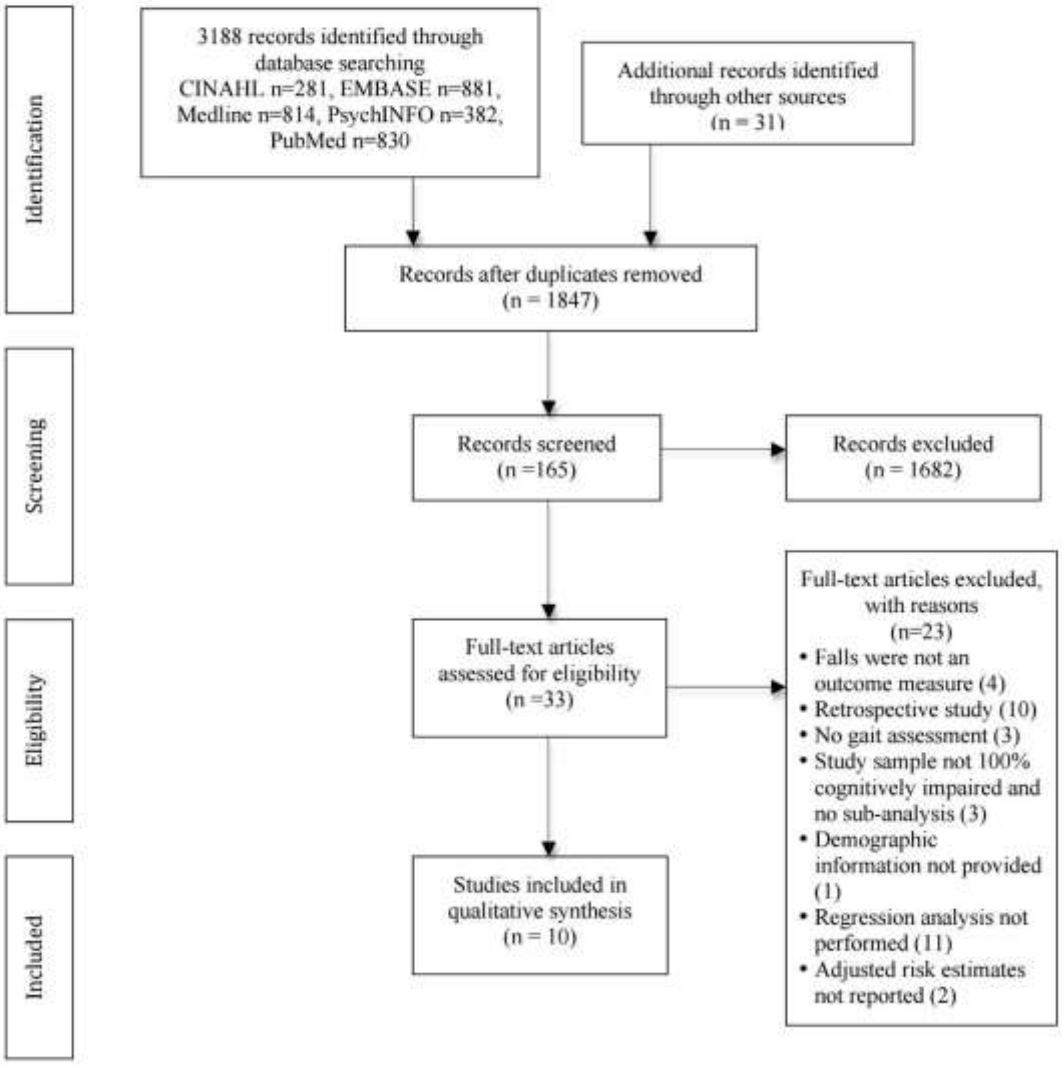

Table 1. Medical Subject Headings and keywords that were used to search the databases.

Dementia group of key terms	Gait group of key terms	Falls group of key terms
Dementia	Gait	Fall risk
Demented	Walking	Accidental falls
Alzheimer's disease	Walk	Falls
Alzheimer disease	Step	Falling
Dementia of Alzheimer's type	Step-length	Fall-related
Multi-infarct dementia	Step-time	Fall risk factor
Multiinfarct dementia	Stride	Fall risk factors
Multi infarct dementia	Cadence	Fall risk assessment
Vascular dementia	Stance	Risk assessment
Frontotemporal dementia	Double support	Risk reduction
Fronto-temporal dementia	Single support	
Senile dementia	Mobility	
Pre-senile dementia	Ambulation	
Presenile dementia		
Dementia with Lewy body		
Diffuse Lewy body disease		
Cognitive impairment		
Impaired cognition		
Mild cognitive impairment		
Pick disease of the brain		

Table 2. Summary of study details for papers included in systematic review (n=10).

Author, year, country	Setting	Type and severity of dementia	Inclusion criteria	Exclusion criteria	Size (%F)	Mean age (SD)	Follow-up duration (months)	Type of fall	Percentage of sample sustaining a fall	Quality Score (/33)*
Gietzelt, 2014, Germany	Specialized nursing home for people with dementia	Severe to most severe CI	Age ≥ 65, TUG >15s, MMSE<24, Recurrent falls, informed consent	Not being able to walk independently	40 (50%)	76.0 (8.3)	2, 4, 8	Any	32.5	21
Schwenk, 2014, USA	CD	Mild to moderate dementia	MMSE 17–26, informed consent, age ≥ 65, no uncontrolled or terminal disorder	n/r	77 (79%)	81.8 (6.3)	3	Any	36.4	22
Taylor, 2014, Australia	CD or from a low-level care facility	Mild to moderate (AD, VD, DLB, as well as mixed dementia types)	Dementia, Age >60 years, community or low-level care facility dwelling, having an identified "person responsible" with 3.5+ h of face-to-face contact/week	Recent stroke, progressive neurodegenerative disorders, insufficient English, end-stage illness	174 (56%)	82.2 (n/r)	12	Any	64	23

Taylor, 2012, Australia	CD	Dementia type not specified	Dementia, age≥60, community-dwelling, and having a 'person responsible' with 3.5+ h of face-to-face contact/week.	Recent stroke, neurodegenerative disorders, insufficient English or known end-stage illness.	63 (46%)	Multiple fallers: 82.5(6.9) Non-multiple fallers: 80.7(6.8)	12	Recurre-nt	54	20
Sterke, 2012, Netherland	Psychogeri-atric nursing home	Moderate to severe dementia; mainly AD	Dementia diagnosis, able to walk at least 10 m independently	n/r	57 (not clear)	81.7 (7)	3	Any	n/r	25
Sterke, 2010, Netherland	Psychogeri atric nursing home	Moderate to severe dementia	A diagnosis of moderate to severe dementia, able to walk independently	Inability to stand/ walk independently, other CIs, no informed consent	61 (64%)	81 (8)	3	Any	26.7	25
Allan, 2009, UK	A mix of CD and residents of care homes.	AD, VAD, DLB, PDD (majority mild-moderate dementia)	Age>65	Unable to perform assessments due to other co-morbidities, MMSE<8, too visually impaired to complete assessments	140 (39%)	AD 79 (5.8), VAD 79 (6.2), DLB 76 (7.1), PDD 72 (6)	12	Any	65.7	23
Pellfolk, 2009, Sweden	Group-dwelling	Any dementia diagnosis	Any diagnosis of dementia	n/r	160 (79%)	83.6 (6.6)	6	Any	40	20

Eriksson, 2008, Sweden	Residential care excluding advanced nursing homes	Any dementia diagnosis	Age>65	n/r	103 (80%)	83.6 (6.3)	6 / residenc e change/ death	Any	62	22
Camicioli and Licis, 2004, Canada	Alzheimer Care Units	AD (moderate to severe)	Possible or probable AD	n/r	42 (86%)	No falls: 82.29 (6.69). Falls: 83.06 (9.57)	Up to 12	Any	43	21

%F, percentage of sample that were females; ACE-R, Addenbrooke's cognitive examination – revised; AD, Alzheimer's disease; CD, community dwelling; CI, cognitive impairment; CNS, central nervous system; DLB, dementia with Lewy Bodies; DM, diabetes; h, hour; m, meter; MMSE, mini mental state examination; n/r, not reported; PDD, Parkinson's disease dementia; SD, standard deviation; TIA, transient ischemic attack; TUG, timed up and go; VD, vascular dementia. *, Quality of reporting assessment was performed using the 33-item scale by Tooth and colleagues. The maximum score is 33, with a higher score indicating greater reporting quality.

Table 3. Summary of significant and non-significant gait and falls associations, adjusted risk estimates, and psychometric properties of tools used to quantify gait for future fall risk.

Author, year, country	Significant gait parameter or characteristic associated with any or recurrent falls	Adjusted risk estimates (95% CI)	Psychometric properties
Outcome: Any fall			
Gietzelt, 2014, Germany	Only the mid-term (4 months follow up duration) prognosis shows values for sensitivity, specificity, PPV and NPV, at the same level.		Sensitivity= 78.2%. Specificity= 71.2%, PPV= 74.8%, NPV= 74.8%.
Schwenk, 2014, USA	Lower 'walking bout average duration'	**'Walking bout average duration': OR=0.79 (0.66-0.95)** Adjusted risk estimates for non-significant variables were n/r.	Using a cut-off value for 'walking bout average duration' <15 s combined with a previous history of falls: sensitivity= 71.5%, specificity= 75.5%.
Taylor, 2014, Australia	No significant gait results	Walking activity: IRR=1.15 (0.77-1.72) Adjusted risk estimates for other gait variables were n/r.	
Sterke, 2012, Netherland	Reduced velocity, stride length, BOS variability, and increased DST	**Velocity: OR=1.22, (1.04-1.43)**	Velocity of 68 cm/s (sensitivity=82%, specificity=52%). Stride length of 85 cm (sensitivity=86%, specificity=52%).

		Stride length: OR=1.19, (1.03-1.40) **BOS variability: OR=1.49, (1.15-1.93)** **DST variability: OR=1.53, (1.05-2.25)** Stride length variability: OR=1.82, (0.30-1.03)	Covariance of 17% for BOS variability (sensitivity=60%, specificity=56%). Covariance of 9% for DST variability (sensitivity=63%, specificity= 51%).
Sterke, 2010, Netherland	POMA-T	**POMA-T: HR=1.08, (1.00-1.17)** POMA-G: HR=1.15, (0.96-1.38)	POMA-T: score of ≤ 21 sensitivity=85%, specificity=56%. PPV=38%. POMA-G: score of ≤ 9 sensitivity=70%, specificity=61% PPV= 37%.
Allan, 2009, UK	No significant gait results	Adjusted risk estimates for non-significant variables were n/r.	
Pellfolk, 2009, Sweden	Out-door walks and assistive devices	**Out-door walks: OR=3.6, (1.4-9.0)** **Using assistive devices: OR=3.2, CI= (1.3-7.5)**	
Eriksson, 2008, Sweden	Being male and walking with mobility aid	**Male & walking with aid: IRR=5.16, (1.72-15.4)** Male & walking without aid: IRR=0.79, (0.22-2.79) Female & walking with aid: IRR=1.54, (0.78-3.05)	
Camicioli and Licis, 2004, Canada	Lower cadence in undistracted walk and higher UPDRS scores	**Cadence: RR=0.96, (0.93-0.99)** **UPDRS: RR=1.14, (1.02-1.28)**	

		Adjusted risk estimates for non-significant variables were n/r.	
Outcome: Recurrent falls			
Taylor, 2012, Australia	Increased DST and step length variability	**DST: OR= 2.007, (1.061–3.794)** **Step length variability: OR=2.181, (1.167–4.076)**	

BOS, base of support; CI, confidence interval; cm, centimeter; DST, double support time; HR, hazard ratio; IRR, incident rate ratio; MT, moderate time; NPV, negative predictive value; n/r, not reported; OR, odds ratio; POMA, performance oriented mobility assessment; POMA-G, POMA-Gait; POMA-T, POMA-total; PPV, positive predictive value; s, second; TUG, timed up and go; UPDRS, Unified Parkinson's Disease Rating Scale. Shaded areas indicate that those assessments were not an objective of the study. The bolded entries in the third column indicate statistical significance.

Table 4. Summary of evaluated gait measures and findings.

	Spatiotemporal gait parameters											**Performance tests**		**Other measures**			
	Vlc	**Cdnc**	**BOS**	**DST**	**SL**	**ST**	**ST /v**	**SL /v**	**STL /v**	**DST /v**	**BOS /v**	**POMA**	**TUG**	**MA**	**UPDRS**	**WA (p)**	**ODW**
Outcome: Any fall																	
Gietzelt, 2014, Germany	n/r											n/s	n/s				
Schwenk, 2014, USA												n/s	n/s			n/s **(s)**	
Taylor, 2014, Australia	n/r												n/r	n/r		n/s ()	n/r
Sterke, 2012, Netherland	**s**	n/s	n/s	n/s	**s**	n/s	n/s	n/s		**s**	**s**						
Sterke, 2010, Netherland												**s**					
Allan, 2009, UK												n/s		n/r	n/r		
Pellfolk, 2009, Sweden														**s**			**s**
Eriksson, 2008, Sweden														**s**			
Camicioli and Licis, 2004, Canada	n/s	**s**	n/s		n/s			n/s			n/s				**s**		

Outcome: Recurrent falls																	
Taylor, 2012, Australia	n/s	n/s		**s**	n/s		n/s		**s**					n/s			

Vlc, velocity; Cdnc, cadence; BOS, base of support; DST, double support time; SL, stride length; ST, stride time; STL, step length; /v, variability; POMA, Performance Oriented Mobility Assessment; TUG, Timed Up and Go; MA, mobility aid; UPDRS, Unified Parkinson's Disease Rating Scale; WA, walking activity; (p), specific walking pattern; ODW, outdoor walking; n/r, not reported; n/s, not significant; s, significant. Shaded areas indicate that those assessments were not an objective of the study.