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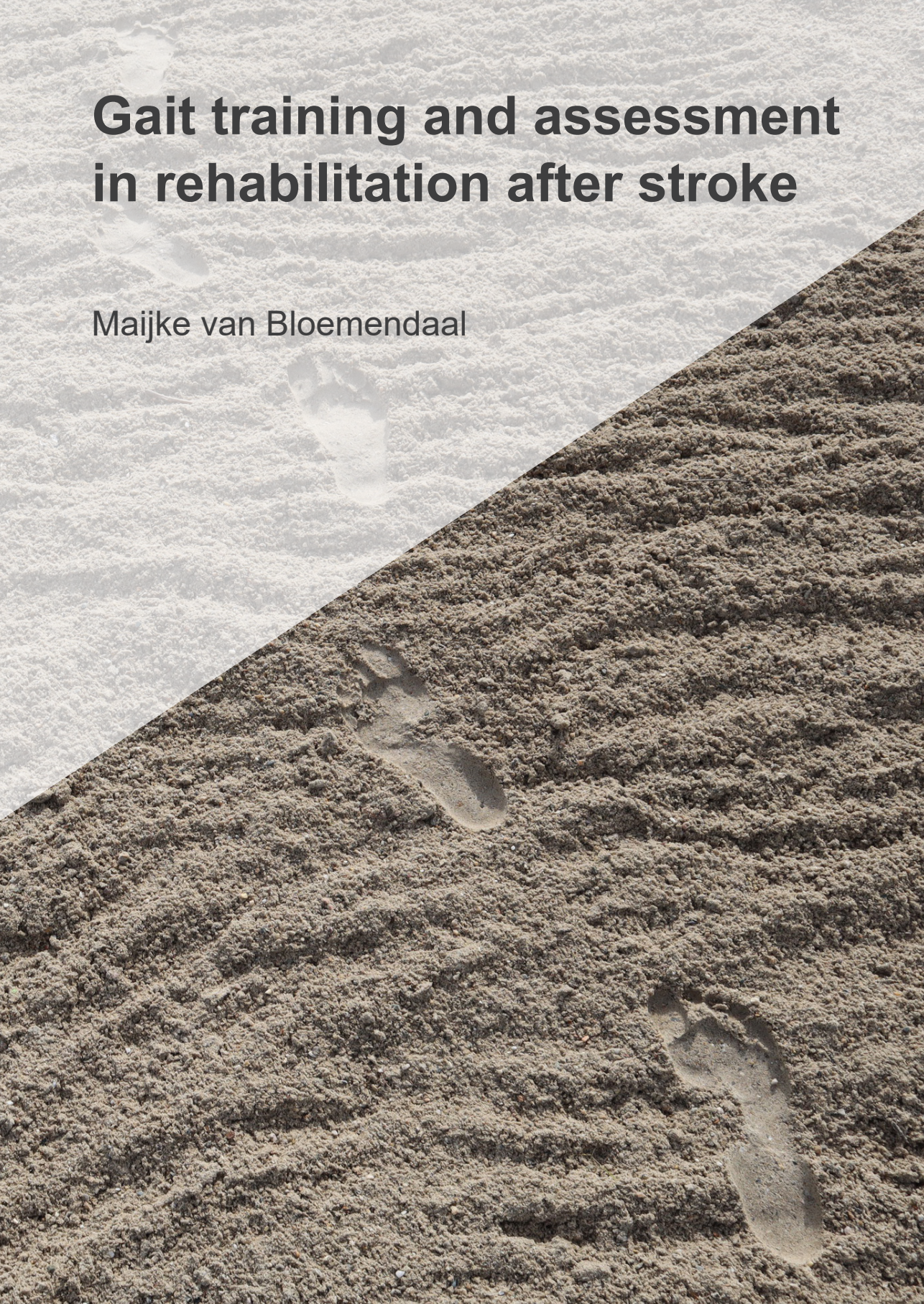

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Gait training and assessment in rehabilitation after stroke

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Tijd en ruimte

Van A naar Beter
Als ik maar niet stil blijf staan
Ga ik van obstakel naar obstakel
Moet ik stapvoets gaan

Kan ik nog omdraaien?
Is er een weg terug?
Wie passeert met mij dalen en bergen?
Vormt voor mij een stabiele brug?

Hopelijk word ik morgen wakker
Is alles achter de rug
Is alles weer vanzelfsprekend
Loop ik, dans, ik spring
Zonder er expliciet over na te hoeven denken
Al is het maar even als vanouds te kunnen ervaren
Hoe vrijwel alles voor mij ging

Maar omdraaien kan ik niet
Ik moet de toekomst tegemoet
Langzaam, meter voor meter
Investeer ik door de tijd
Vorder ik gestaag en houd ik mij voor:
Morgen gaat het beter

M. van Bloemendaal

Contents

Chapter 1

General introduction

The impact of stroke on walking

Approximately 40,000 people in the Netherlands and 16.9 million people worldwide sustain a stroke (cerebrovascular accident) each year.[1,2] There is a large variety in the clinical presentation of stroke, with the functional consequences of stroke depending on the stroke characteristics (mainly stroke location and severity) and age.[3-6] About two-thirds of the stroke survivors experience difficulty with walking immediately after stroke.[7,8]

"Will I ever walk like before?"

I have been asked this question several times by persons after stroke during physiotherapy sessions. A very understandable question, because limited walking ability has major consequences for daily-life functioning, independency, social participation, and quality of life.[9-12] In addition, stroke survivors have an increased fall risk (factor 1.4 to 4) and most falls are caused by loss of balance while walking.[13-15] Because walking is essential in daily life, rehabilitation treatment that aims to improve walking ability is important for people who are unable to walk independently after stroke, as well as for their relatives.[10,16,17] Hence, the majority of stroke survivors with limited walking ability enter an inpatient or outpatient rehabilitation program, as provided by rehabilitation centres. Nevertheless, only 60 to 80% of all stroke survivors eventually regain independent ambulation.[7,9,10,18,19]

Walking in everyday life requires several critical elements of gait *capacity* and an adequate gait *pattern*.[20] Gait capacity is defined as the capacity to walk and encompasses elements such as walking independency, walking endurance, walking balance, walking adaptability, and gait speed.[20] All of these elements of gait capacity can be affected after stroke.[20] The gait pattern, which is the way someone walks, can be described in different characteristics of gait, encompassing the spatiotemporal gait parameters, the kinematics and kinetics, and the muscle activation. The gait pattern may be seriously affected mainly due to impaired leg motor control after stroke.[21-23] Gait pattern impairments may have a major impact on gait capacity, because they often increase energy cost due to reduced gait efficiency[24-27] and lead to balance problems and increased risk of falling.[17,28-30] In addition, asymmetric loading of the limbs in favour of the non-paretic leg may lead to loss of bone mass density on the paretic side[31-33] and signs of overloading (e.g. joint or muscle pain or even osteoarthritis) on the non-paretic side.[13,33] Furthermore, many people after stroke experience that walking is no longer an automatic process, but requires constant attention which is exhausting and complicates the performance of dual tasks.[34] Moreover, a visibly affected gait pattern can affect the mental wellbeing of people after stroke.[35]

The persistent consequences of stroke, for both gait capacity and gait pattern, highlight the importance of studies that aim to enhance post-stroke gait recovery.

Gait pattern impairments and recovery after stroke

The upper motor neuron syndrome caused by stroke results in a combination of

sensorimotor impairments including muscle weakness, impaired selective motor control, reduced trunk and balance control, spasticity, and proprioceptive deficits that interfere with normal gait.[36-39] The resultant hemiparetic gait pattern is a mixture of maintained sensorimotor functions, sensorimotor deficits, and compensatory mechanisms; as such, there is great diversity in post-stroke gait patterns.[36] It is, therefore, important to identify and document gait impairments per individual to determine which interventions this person may benefit from.[36]

Gait can be defined in kinematic (motions) and kinetic (forces, moments, and power) terms during the gait cycle (moment of heel strike to the next heel strike of the ipsilateral leg). Typical kinematic gait deviations and adaptations seen after stroke during the gait cycle are: (1) a lack of ankle dorsiflexion and knee flexion during the swing phase, often compensated by a circumduction movement of the pelvis and trunk to clear the foot from the ground; (2) limited ankle dorsiflexion and knee hyperextension during the (mid-) stance phase; and (3) limited ankle plantarflexion and hip extension during the push-off. In addition, various kinetic gait deviations have been reported after stroke, such as reduced loading at initial contact and reduced ankle plantarflexion moment and push-off during late stance on the paretic side,[36,40-42] and compensatory generation of ankle power on the non-paretic side.[36,43,44] In terms of muscle activation patterns, people after stroke often exhibit pathological co-activations, i.e. simultaneous recruitment of muscles at multiple joints resulting in a stereotypical ('synergistic') movement patterns.[45-47] Muscle activation can be disturbed by premature onset, prolonged duration, and abnormal peaks of muscle activity compared to the normal activation pattern.[41,42,46,48] Although electromyographic abnormalities are most pronounced in the paretic leg, muscle activation patterns of the non-paretic leg may also display some clear abnormalities.[41]

Spatiotemporal gait parameters are most often used to describe the pathological gait pattern after stroke. Spatiotemporal gait parameters include all distance (spatial) and time (temporal) parameters related to the gait cycle (Figure 1.1). These parameters are the result of the kinetic and kinematic gait characteristics of an individual. Spatiotemporal adaptations after stroke are decreased gait speed, shortened and uneven step lengths, increased step width, increased double support time, and reduced cadence.[36,49] Given the mostly unilateral impairments after one-sided stroke, gait *asymmetry* is usually observed due to abnormalities on the paretic side and compensatory motions on the non-paretic side.[30,50-54] Spatiotemporal measures of gait symmetry reflect the similarity of the distance and time parameters between both legs. Swing time asymmetry and step length asymmetry are prevalent in 56 to 82% and 44 to 62% of the stroke population, respectively.[30,50-52] Stroke survivors usually have a reduced single-leg stance time and increased swing time on the paretic side (temporal asymmetry).[43,55-58] Spatial asymmetry after stroke is often characterised by a shorter step length of the non-paretic leg, although a shorter step length of the paretic leg is also regularly seen.[59] Step length symmetry is considered to be a good measure of gait symmetry. In this thesis, it is seen as a (surrogate) outcome for

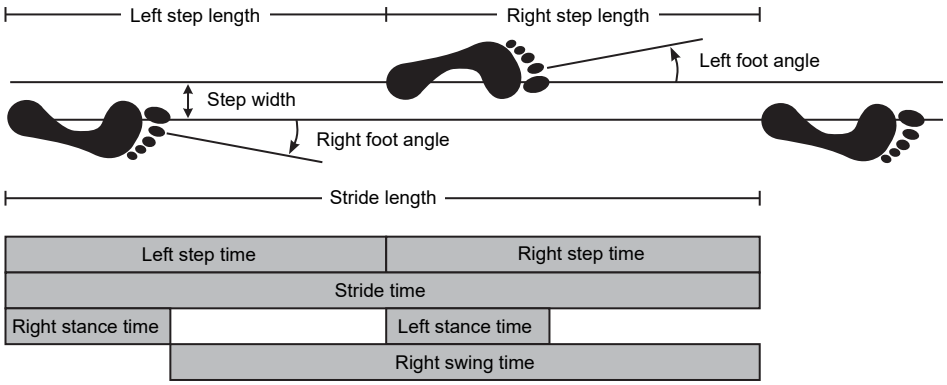

Figure 1.1. Representation of spatial and temporal gait parameters (adapted with permission from Vaughan et al.[61]).

restitution of motor function after unilateral stroke, because it is strongly influenced by the restoration of motor control of the paretic leg in terms of its kinematic (sufficient hip flexion, knee extension, and ankle dorsiflexion) and kinetic (sufficient stance stability, ankle power, and propulsive impulse) characteristics.[16,36,60]

Recovery of the gait pattern after stroke greatly depends on spontaneous sensorimotor recovery, particularly of the paretic leg. This is a complex process, and the mechanisms driving these improvements are still debated.[4,62] Most improvements occur within the first three to four weeks post stroke (sub-acute phase), which then level off with the passing of time.[6,63] There is growing evidence that further improvement of the gait pattern after the first 12 weeks post stroke should not be expected.[7,64-68] This supports the importance of early gait rehabilitation during which neurological recovery of the paretic leg is most pronounced and the 'window of opportunity' to restore spatiotemporal gait symmetry is supposed to be optimal.[65,66,69-72] However, current evidence that the gait pattern or sensorimotor impairments after stroke can be influenced by training (or any other intervention) is very limited.[4,72] In contrast, improvement of gait capacity may be achieved many months or even years after stroke, based on the optimisation of compensatory mechanisms and perhaps the re-activation of latent sensorimotor functions (e.g. related to 'learned non-use').[4,73] Therefore, the next paragraph will address the efficacy of gait rehabilitation with regard to both the gait capacity and the gait pattern after stroke.

Efficacy of gait training interventions after stroke

Gait training forms a major part of physiotherapy for stroke survivors in almost every clinical setting and refers to a wide range of physiotherapy interventions, all aimed at promoting the gait capacity and/or gait pattern after stroke. Interventions mainly aimed at improving gait capacity comprise overground walking training on even and uneven surfaces, (dynamic) balance training, dual-task training, (split-belt) treadmill training with and without body-

weight support or robotic assistance, and virtual-reality training.[28,66,74-77] Interventions mainly aimed at improving the gait pattern comprise traditional neurophysiological techniques (e.g. neurodevelopmental treatment [NDT] and proprioceptive neuromuscular facilitation [PNF]), motor learning approaches, overground gait training (referring to physiotherapists' observation and cueing of an individual's gait pattern along with related exercises), water-based exercise, electrical stimulation, electromyographic biofeedback, electromechanical and robotic devices, motor imagery, and brain-computer interfaces (not yet used in clinical practice).[28,66,68,76-78]

Although most types of gait training aimed at gait capacity seem to be beneficial beyond 'natural' functional recovery, none of the above-mentioned interventions seems to be superior. Yet, a combination of different interventions may be more effective than overground gait training alone for improving gait capacity and gait speed after stroke.[66-68,75,77,79] Trunk, muscle strength, and cardiorespiratory training seem to be important as supportive therapies to improve general physical status and trunk control.[28,80] There is high-quality evidence for physiotherapy interventions, amongst which gait training aimed at gait capacity, favouring high repetitive task-oriented and task-specific training in all phases after stroke.[66,81,82] Effects are mostly restricted to the actually trained skills and activities.[66] Evidence of the optimal dose and intensity of physiotherapy is limited by substantial heterogeneity and does not result in robust conclusions.[67,83,84]

Currently, there is insufficient evidence for the efficacy of any training intervention to improve the gait pattern or step length symmetry after stroke. Of 29 randomised controlled trials evaluating step length symmetry in stroke survivors, 13 reported statistically significant positive changes in favour of the experimental intervention (PubMed search up to August 2020).[85-113] These studies compared conventional gait training to several specific gait training interventions (i.e. robotics,[86-89] motor imagery,[85] robotic body weight supported treadmill training,[90] conventional treadmill training,[91] repetitive transcranial magnetic stimulation,[92,93] lower leg mono-channel neuromuscular electrical stimulation,[94] high-intensity training,[96] electrical stimulation of the tibialis anterior muscle combined with a rocker board,[95] and sensory feedback[97]). However, the reported group differences were generally moderate and thresholds for minimal clinically important differences remained too ambiguous to put the observed changes into the right perspective.[85-97] In comparison, the 16 studies that reported no statistically significant differences for step length symmetry in favour of the experimental group investigated the effect of conventional training combined with paretic leg weight load,[98] targeted spatiotemporal asymmetry training,[99] error augmentation or minimisation,[105] turning-based treadmill training,[112] high-variability and intensity training,[101] robotics,[103] body weight supported treadmill training,[110,111] Pilates,[113] compelled weight-shift therapy,[109] visual feedback,[106,107] high-intensity training,[100] task-oriented circuit class training with motor imagery,[102] rhythmic auditory stimulation,[104] and action observation training.[108] Remarkably, for a number of interventions, both positive and negative results were found in the literature. There are three possible explanations for the observed lack of

evidence. First, most intervention studies were underpowered, which increases the risk of false negative outcomes.[114] Second, many intervention studies included individuals in the chronic phase after stroke,[85,86,90-94,96,99,101,103,105,107,109-113] during which (further) improvement of the gait pattern is unlikely.[7,65,70,71] Third, only a few intervention studies focused primarily on restoring gait symmetry.[90,91,93,97-99,104,105,112] Nevertheless, improving spatiotemporal gait symmetry remains an important issue, because of the negative functional consequences of asymmetry, including increased risk of falls and injuries, reduced gait efficiency, poor aesthetics, risk of muscle shortening, joint deformation, and pain complaints.[17,30,35,51,115] New techniques such as multi-channel functional electrical stimulation may, therefore, perform better by their ability to impose an adequate gait pattern.

Post-stroke gait training assisted by functional electrical stimulation

Muscle contraction of paralysed or paretic muscles can be achieved by applying electrical currents to the intact peripheral motor nerves.[116] When electrically elicited muscle contractions lead to functional movements, the technique is called functional electrical stimulation (FES).[116] FES can be applied as an orthotic device, whereby the benefits occur whilst the device is used, or as a therapeutic intervention whereby the benefits persist once the FES has ceased.

Orthotic application of FES implies that an individual wears the device during relevant activities. This can either entail an external or an implantable FES device. FES of the common peroneal nerve and tibialis anterior muscle (‘peroneal FES’) is most frequently used as an alternative to an ankle foot orthosis to provide foot clearance during the swing phase of gait by assisting ankle dorsiflexion. There is evidence that orthotic application of peroneal FES improves gait-related outcomes (e.g. gait pattern, gait speed, walking distance, and physical activity) in all stages after stroke compared to no treatment.[117-120] Results of a recent study suggest that implantable peroneal FES may have benefits on knee stability, ankle plantar flexion power, and propulsion compared to an ankle foot orthosis, because the stiffness of an ankle foot orthosis hampers normal ankle motion.[121] Furthermore, several studies have shown that stroke survivors are generally satisfied with FES and prefer this treatment option over an ankle foot orthosis because of experienced gait efficiency, stability, safety, quality, and distance. In addition, FES is preferred because of experienced comfort, appearance, and ability to move the ankle freely during non-gait-related activities.[120,122-130] Nevertheless, based on randomised controlled trials using objective outcomes, orthotic FES seems to be equally effective compared to an ankle foot orthosis for improving gait-related outcomes.[129-134]

The therapeutic effect of FES refers to changes in the gait pattern or gait capacity that persist after the FES treatment.[119] Several studies investigated the efficacy of FES alone or FES combined with other interventions, such as leg-cycling or tilt-table stepping, to improve gait.[129] Most studies evaluated the effects of peroneal FES and evaluated its effects in the chronic phase after stroke.[79,118-120,125-129,135-140] The evidence for the efficacy of solely

applying therapeutic FES is limited by a small number of low-quality studies. Therefore, it remains unknown whether therapeutic FES enhances gait recovery.[79,118-120,129,139-144] Multi-channel FES (MFES) – referring to electrical stimulation applied to lower and upper leg muscles – may be more effective than peroneal FES in normalising the gait pattern by compensating for thigh as well as dorsiflexor muscle weakness. Moreover, starting therapeutic MFES in the sub-acute phase after stroke may be effective for recovery of the gait pattern through enhancing spontaneous neurological recovery and promoting adequate compensatory motor strategies. To our knowledge, four controlled studies have investigated the effectiveness of therapeutic MFES starting in the sub-acute phase after stroke.[141-144] These studies reported positive outcomes on gait speed, motor function, balance control, gait capacity, and functional abilities of daily living in favour of MFES compared to conventional gait training. However, these studies did not investigate the efficacy of MFES for the restoration of gait symmetry; and three out of four studies were not dose-matched and applied MFES in a supine position.[141-143] They all had a high risk of bias by incomplete reporting of subject selection and results,[141,144] unblinded outcome assessments,[142,144] loss to follow-up,[143] and imprecision of effect estimates due to small sample sizes and poor statistical analyses.[141-144] Therefore, it remains unknown whether MFES is effective for promoting the gait pattern early after stroke. Further research is needed to obtain insight in the efficacy of gait training assisted by MFES on step length symmetry, spatiotemporal gait parameters, and gait capacity in the first three months after stroke.

Gait assessment after stroke

To evaluate and better understand treatment benefits of gait training after stroke, proper assessment of gait capacity and gait characteristics is crucial.[16,36] Furthermore, it is important to assess these outcomes from a clinical perspective to identify gait deviations, guide clinical decision making, customise treatment, and monitor individual progress.[16,36] To assess gait capacity and gait characteristics properly, feasible measurement instruments with adequate measurement properties (i.e. valid, reliable, reproducible, and responsive) are required.[16,36]

Many measurement instruments to assess gait capacity are available, such as tests to assess walking endurance, walking balance, and walking independency. However, a clear overview of gait capacity tests, including information about their measurement properties in stroke survivors, is lacking. Such an overview can provide clinicians and researchers with a guidance to select the optimal measurement instruments.

Gait characteristics (e.g. step length, cadence, foot clearance) are often assessed by observation, but objective, quantitative measures (i.e. gait analysis) are required to accurately assess the (underlying) impairments. The methodology available for gait analysis covers a large number of assessment tools. Three-dimensional gait analysis is considered the gold standard. However, three-dimensional gait analysis is time consuming, labour

intensive, and expensive. This sophisticated assessment procedure is abundant if the main interest is to measure spatiotemporal gait parameters. Electronic walkways are a cheaper alternative and easier to apply, but these bring about practical issues as they force people to walk within a relatively narrow bandwidth of the carpet and require them to walk on and off the carpet.[145] Other alternatives to measure spatiotemporal gait parameters are low-cost systems that use a single camera setup, footswitches, accelerometers, gyroscopes, and inertial measurement units. However, results on the accuracy for obtaining spatial parameters are inconsistent or absent and it is questionable if some of these systems are reliable in persons with gait deviations (e.g. forefoot contact at initial contact).[145-156] Hence, there remains a need for low-cost, reliable, and simple alternatives for three-dimensional gait analysis to measure spatiotemporal gait parameters.

General aims and outline of the thesis

This thesis has two general aims. First, to increase the methodological knowledge of gait assessment post stroke. And second, to determine whether gait training assisted by MFES early after stroke is feasible and enhances the recovery of spatiotemporal gait symmetry and gait capacity.

This thesis consists of two parts to achieve these aims. Part one focuses on measurement instruments for gait assessment in stroke survivors (Chapters 2 to 5). Part two describes the design and results of a pilot randomised controlled trial investigating the feasibility and preliminary efficacy of gait training assisted by MFES early after stroke (Chapters 6 and 7).

Chapter 2 provides a comprehensive overview of gait tests applied in people after stroke, including their measurement properties, using the International Classification of Functioning, disability and health (ICF) model as a framework. Subsequently, Chapters 3 and 4 describe the validity, reproducibility, and measurement error of two gait capacity tests: the modified Shuttle Walk Test (*Chapter 3*) and the Functional Gait Assessment (*Chapter 4*). *Chapter 5* describes the measurement properties of a new low-cost spatiotemporal gait analysis system (SGAS) that can be used to analyse spatiotemporal gait parameters, from which spatiotemporal gait symmetry can be derived.

Chapter 6 describes the study protocol of a pilot randomised controlled trial, the GAFESS study, investigating whether gait training assisted by MFES early after stroke is feasible and enhances the recovery of spatiotemporal gait symmetry and gait capacity. GAFESS stands for Gait Assisted by multi-channel Functional Electrical Stimulation in early Stroke rehabilitation. *Chapter 7* presents the results of this randomised controlled trial.

Finally, *Chapter 8* contains the general discussion in which the results of the studies are integrated, and strengths and limitations are addressed as well as implications for future research and clinical practice.

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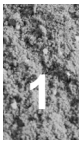
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Chapter 2

Walking tests for stroke survivors: a systematic review of their measurement properties

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Abstract

Purpose. To provide an overview of walking tests including their measurement properties that have been used in stroke survivors.

Method. Electronic databases were searched using specific search strategies. Retrieved studies were selected by using specified inclusion criteria. A modified consensus-based standards for the selection of health status measurement instruments (COSMIN) checklist was applied for methodological quality assessment of the included studies. A quality assessment for statistical outcomes was used to assess measurement properties of the walking tests. Tests that were included were categorized according to the framework of the international classification of functioning, disability and health (ICF).

Results. Thirty-two studies, evaluating 23 walking tests, were included. The tests assessed walking using the outcome measures of walking speed, walking distance, functional ambulation and walking on different surfaces. The methodological design and statistical methods of most studies evaluating reliability and criterion validity were sufficient, and found the outcome measures to be reliable and valid. However, data on measurement error, minimal important difference and minimal important change were lacking and responsiveness was correctly evaluated in one study only.

Conclusions. Many walking tests have been clinimetrically evaluated in stroke survivors. Most walking tests were found to be reliable and valid.

Introduction

In the acute phase, 60–80% of stroke survivors experience walking limitations.[1,2] Only upto 74% of chronic stroke survivors regain sufficient walking ability to walk outside their homes.[3] Walking ability after stroke is associated with activities of daily living, health-related quality of life and the possibility of returning home after rehabilitation.[4-6] Hence, regaining independent walking at home and in the community is important and often a primary goal of rehabilitation after stroke.[7-9]

It is essential for clinicians and researchers to use feasible, reliable, valid and responsive performance-based walking tests to assess a patient's walking ability, track changes over time and evaluate the effectiveness of interventions.[10,11] Many walking tests are available, but only some of these have been studied in terms of measurement properties. Several reviews have surveyed walking tests used to assess walking in stroke survivors.[12-15] Mudge and Stott[12] provided an overview of walking tests assessing mobility, including walking, without describing the measurement properties. Tyson and DeSouza[14,15] reviewed the measurement properties of ordinal scales and functional performance tests that assess balance and walking. However, their review included only three studies involving scales and tests that exclusively assess walking. Tyson and Connell[13] reviewed the measurement properties and clinical utility of walking tests to assess walking and mobility in patients with neurological conditions in general. However, the impact of different neurological conditions on mobility and walking in specific could be diverse. Furthermore, mobility and walking enclose different constructs and, consequently, many different tests are being used to assess these different constructs. Although reviews on this subject have been published[12-15], a clear overview of available walking tests including information about their measurement properties in stroke survivors is lacking. Such an overview could guide clinicians and researchers in choosing the right walking test for their specific aim which meets the measurement requirements. The purpose of the present review was to provide an overview of walking tests used in stroke survivors including information about the tests' measurement properties in terms of reliability, validity and responsiveness.

Method

Literature search

The electronic databases PubMed, CINAHL, EMBASE and Cochrane Controlled Trial Register (1966 – 6 January 2011) were searched by one reviewer (Maijke van Bloemendaal) using database specific search strategies (for Pubmed search see Supplement 2.1). The search strategy consisted of MeSH terms and free text words divided into four components: (1) condition ("stroke" and synonyms); (2) outcome ("walking" and synonyms); (3) walking tests (synonyms and abbreviations); and (4) a modified search

filter for measurement properties.[16] In addition, reference lists of included studies, conference abstracts and relevant reviews[12-15] were screened for potentially eligible studies. Studies were selected by two independent reviewers (Maijke van Bloemendaal and Alexander T.M. van de Water) using the following criteria: (1) participants were adult stroke survivors; (2) the walking tests that were described measured walking; (3) the objective of the studies was to evaluate measurement properties (reliability, validity and/or responsiveness); (4) studies were published in English, German, French or Dutch; and (5) a full text article was available. Walking was defined according to the International Classification of Functioning, Disability and Health (ICF) which classifies walking as a second-level category (d450) within the first-level category of mobility (d4), part of the activities and participation chapter.[17] The walking category includes the following third-level categories: “walking short distances (<1 km)” (d4500), “walking long distances (>1 km)” (d4501), “walking on different surfaces (also uneven or moving)” (d4502), “walking around obstacles” (d4503), “walking other specified” (d4507) and “walking unspecified” (d4508). Studies were excluded when the walking tests assessed walking impairments, such as stride or cadence. If disagreement between reviewers persisted after discussion, a third reviewer (Astrid M.J. Kokkeler) was consulted. Data (study size, specific selection criteria or characteristics of participants, number of repetitions, interval between repetitions, testing period, number of raters, walkway description and remarks) was extracted by one reviewer (Maijke van Bloemendaal).

Methodological quality assessment

The “consensus-based standards for the selection of health measurement instruments” (COSMIN) checklist was used to determine the methodological quality of the studies included, and to evaluate the appropriateness of the statistical methods (Table 2.1).[18-20] Content validity of the COSMIN checklist has been ensured by a worldwide

Table 2.1. Qualitative data analysis to determine measurement properties

Study element	Assessment	Judgement		
Methodological design	COSMIN checklist adapted for walking tests (design requirements of the boxes)[18,19]	++ + ++ + 0	Excellent: Good: Fair: Poor:	100% items present ≥70% items present 21-69% items present AND no major flaw ≤20% items present OR major flaw
Statistical method	COSMIN checklist adapted for walking tests (statistical methods of the boxes)[18,19]	+ 0	Meeting the COSMIN checklist criteria Not meeting the COSMIN checklist criteria	
Completed when statistical method is positive:				
Statistical outcomes	Table 2.2	+ -	Good measurement property of the walking test Poor measurement property of the walking test	

Delphi study among a large panel of experts.[20] The COSMIN checklist was chosen for its comprehensiveness and was considered the best assessment tool available for this type of study. The COSMIN checklist was adapted for use on "walking tests" by substitute "health-related patient-reported outcomes" in "measurement instruments" and only the methodological part of the checklist was used. The COSMIN checklist consists of nine sub-checklists for different measurement properties (i.e. internal consistency, reliability, measurement error, content validity, structural validity, hypothesis testing, cross-cultural validity, criterion validity and responsiveness) and two sub-checklists to determine the interpretability and generalisability of the studies. Two independent reviewers (Maijke van Bloemendaal and Alexander T.M. van de Water) performed the methodological quality assessment, and if disagreement persisted after discussion, a third reviewer (Astrid M.J. Kokkeler) was consulted. To quantify inter-rater agreement concerning the methodological quality assessment, using the COSMIN checklist Cohen's Kappa (κ) was calculated on the original scores of the two reviewers (before discussion). The following interpretation was used: 0.01–0.20 means slight agreement; 0.21–0.40 means fair agreement; 0.41–0.60 means moderate agreement; 0.61–0.80 means substantial agreement; and 0.81–0.99 means almost perfect agreement.[21-23] The methodological quality of a study was rated as described in Table 2.1 and statistical methods were evaluated using the COSMIN checklist.[18,19]

Statistical quality assessment to interpret measurement properties

A quality assessment for the statistical outcomes, based on the versions of Schellingerhout et al.[24] and Van der Leeden et al.[25], was used to interpret the measurement properties of the walking tests (Table 2.2). If the statistical methods had been correctly applied, the statistical outcomes of these methods were evaluated with the quality assessment to draw conclusions about the measurement properties of the walking tests. Recommended cut-off values of statistical outcomes were used to determine if the walking test had good (+) or poor (−) measurement properties.[24,25] In evaluating validity, we only took the associations between the walking tests and components of walking into account.

Results

Walking tests

The electronic searches revealed 971 studies, and after initial selection based on title and abstract, 101 were potentially eligible (Figure 2.1). After full text selection, 30 studies were included for data analysis. Screening reference lists of the included articles resulted in two new relevant studie.[26,27]

Table 2.2. Quality of the statistical outcomes to determine measurement properties

Measurement property[a]	Rating[a]	Quality Criteria
Reliability		
Internal consistency	+	Cronbach's α between 0.70 and 0.95 OR KR-20 between 0.70 and 0.95 OR (goodness of fit if the fit was good on scale level or for 80% of the items (i.e., 2 not significant, person separation ≥0.70, lnFit statistics between 0.70 and 1.3) AND item calibration ≥80% of the inter-item differences were ≥0.15 logits)
	-	Cronbach's α <0.70 or >0.95 OR KR-20 <0.70 or >0.95 OR (no goodness of fit OR poor item calibration)
Reliability	+	ICC >0.70 OR Κ >0.70
	-	ICC ≤0.70 OR Κ ≤0.70
Measurement error[b]	+	MIC > SDD OR MID > SDD OR MIC outside the LoA
	-	MIC ≤ SDD OR MID ≤ SDD OR MIC equals or inside LoA
Validity		
Content validity	+	The target population considers all items in the questionnaire to be relevant AND considers the questionnaire to be complete
	-	The target population considers items in the questionnaire to be irrelevant OR considers the questionnaire to be incomplete
Construct validity • Structural validity	+	Factors should explain ≥50% of the variance
	-	Factors explain <50% of the variance
• Hypothesis testing	+	(Correlation with a walking test assessing the same construct ≥0.50 OR ≥75% of the results were in accordance with the hypotheses) AND correlation with related constructs was higher than with unrelated constructs
	-	Correlation with a walking test assessing the same construct <0.50 OR <75% of the results were in accordance with the hypotheses OR correlation with related constructs was lower than with unrelated constructs
• Cross-cultural validity	+	Convincing arguments are presented to prove that the walking test was correctly translated or culturally adapted AND the correlation between the translated or culturally adapted walking test and original walking test was ≥0.70
	-	Unconvincing arguments are presented that the walking test was correctly translated or culturally adapted OR the correlation between the translated or culturally adapted walking test and the original walking test was <0.70
Criterion validity (predictive or concurrent)	+	Correlation with standard was ≥0.70 OR AUC ≥0.70 OR no statistically significant differences between walking test and golden standard were found OR sensitivity and specificity ≥0.70
	-	Correlation with standard was <0.70 OR AUC <0.70 OR statistically significant differences between outcome measure and golden standard were found OR sensitivity and specificity <0.70
Responsiveness		
Responsiveness	+	(Correlation with a walking test assessing the same construct ≥0.50 OR ≥75% of the results were in accordance with the hypotheses OR AUC ≥0.70 OR sensitivity and specificity ≥0.70) AND correlation with related constructs was higher than with unrelated constructs
	-	Correlation with a walking test assessing the same construct <0.50 OR <75% of the results were in accordance with the hypotheses OR AUC <0.70 OR sensitivity and specificity <0.70 OR correlation with related constructs was lower than with unrelated constructs

Table 2.2 continues on the next page.

Table 2.2. *Continued*

Measurement property[a]	Rating[a]	Quality Criteria
Floor or ceiling effects	No	≤15% achieved the highest OR lowest possible score
	Yes	>15% achieved the highest OR lowest possible score

+, measurement property; -, no measurement property; *open window*, no justified statistical method;
α, alpha(s); KR-20, Kuder-Richardson formula(s); ICC, intraclass correlation coefficient;
K, Cohen's (Weighted) Kappa; SDD, smallest detectable difference; MIC, minimal important change;
MID, minimal important difference; LoA, limits of agreement;
AUC, area under the receiver operating characteristics (ROC) curve.
[a] If the statistical method does not meet the COSMIN criteria, there is no justified statistical outcome, so the window will be empty.
[b] Standard error of measurement (SEM) is a correct statistical method to assess measurement error, but there is no evidence for the interpretation of this outcome. Therefore the SEM is displayed but not coupled with the statistical outcome.

The thirty-two included studies described 23 walking tests which could be categorised according to the ICF as "walking short distances (<1 km)" and "walking on different surfaces". Within the ICF category of "walking short distances (<1 km)" the authors assigned "walking distance", "walking speed" and "functional ambulation" as ICF qualifiers (Table 2.3). None of the walking tests described were classified in the ICF categories of "walking long distances (>1 km)", "walking around obstacles" and "walking, other specified and unspecified". The included studies reported most walking tests to be easy to use and to require little time to administer. However, most walking tests require a walkway, ranging in length from 5[26,28,29] to 122 m[30]. Costs of the walking tests were reported in four studies and were considered to be low.[31-34]

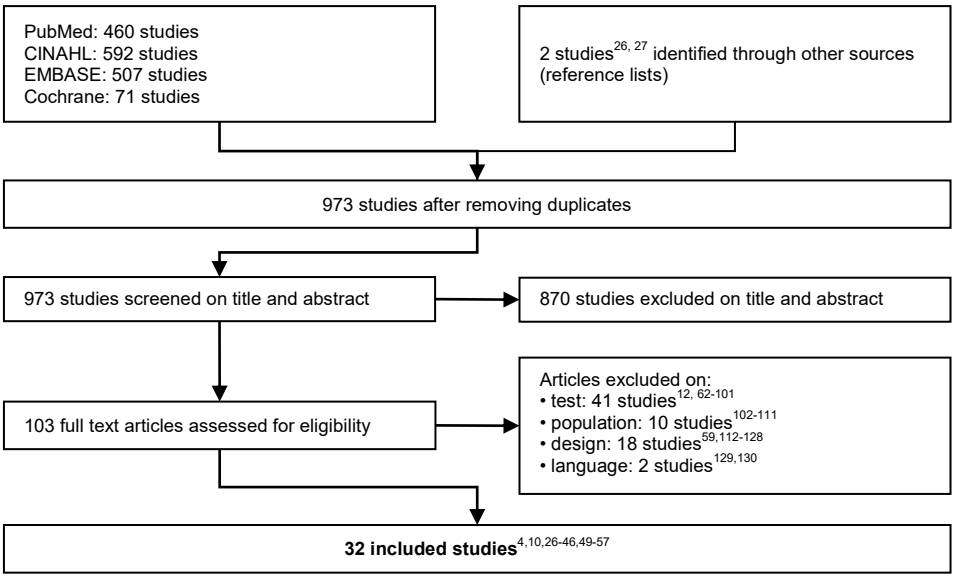

Figure 2.1. Flow chart of study selection.

Table 2.3. Evaluated walking tests

ICF category	Walking test	Abbreviations	Reference
Walking short distances			
Walking distance	Two minute Walk Test	2minWT	30
	Six minute Walk Test	6minWT	10, 27, 30, 37, 38, 49
	Twelve minute Walk Test	12minWT	27, 30
Walking speed	Four metre Comfortable Walk Test	4mCWT	27
	Five metre Walk Test unspecified	5mWT	50
	Five metre Comfortable Walk Test	5mCWT	28, 45, 46, 51, 52
	Five metre Fast Walk Test	5mFWT	45
	Six metre Comfortable Walk Test	6mCWT	53
	Ten metre Comfortable Walk Test	10mCWT	31, 37, 39, 40, 45
	Ten metre Fast Walk Test	10mFWT	4, 31, 37, 45
	Ten metre Walk Turn Test	10mWTT	26, 28, 29
	Thirty metre Comfortable Walk Test	30mCWT	40
	Footswitch System	FS	32, 35, 54
	Accelerometer	AM	41, 42
	Pedometer	PM	33, 41
Functional ambulation	Six minute Walk Test in Different Environments	6minWTDE	43
	Three hundred metre Walk Test in community	300mWT	39
	Functional Ambulation Categories	FAC	28, 31, 34, 46
	Functional Ambulation Classification Hospital Sagunto	FACHS	44
	Dynamic Gait Index	DGI	36, 55
	Dynamic Gait Index 4 items	DGI-4	36
	Functional Gait Assessment	FGA	36, 56
Walking on different surfaces	Six metre Walk Test on Parquet and Carpet	6mWTPC	57

Study characteristics

The populations and methodological designs of the included studies are described in Table 2.4. A combined total of 1093 participants were assessed and at least 27% of them used a walking device. Measurements were repeated with reassessment intervals varying from a few minutes[26,35] to 25 weeks[36]. Approximately one-third of the studies[27-29,33,36-43] included stroke survivors in the chronic phase (more than 6 months post stroke).

Methodological quality of the included studies

The methodological design, statistical methods and statistical outcomes of the included studies are listed in Table 2.5. Prior to discussion, moderate agreement was found between the reviewers (κ=0.51) as regards the assessment of methodological quality using the COSMIN checklist. Disagreement between reviewers was mainly found for the items “adequate sample size”, “appropriate time interval” and “stability of the participants of the construct to be measured”. After discussion, the third reviewer was consulted for one study.[4] According to the COSMIN checklist, most studies demonstrated fair to good generalisability and interpretability, except three which showed poor interpretability.[30,42,44] While reliability and criterion validity were the most commonly evaluated measurement properties, responsiveness was correctly evaluated for the Functional Ambulation Categories[34] only, and correct data on measurement error were not reported at all.

Most studies had a suitable methodological design to evaluate the measurement properties of the instruments studied (Table 2.5). Overall, the sample size, handling of missing data and independency of administration were moderately described. No measurement properties were available for the Two minute Walk Test[30], due to the poor methodological design (Table 2.5). Twenty-four studies used a suitable statistical method to assess reliability and criterion validity (i.e. concurrent or predictive). According to the COSMIN criteria, only one study used appropriate statistical methods to evaluate responsiveness (Table 2.5).[34]

Measurement properties of the walking tests

The statistical outcomes for reliability and criterion validity were above the thresholds (Table 2.2), indicating good measurement properties found in most of the studies (32 of 35 statistical outcomes). No measurement properties were available for the Five metre Fast Walk Test[45], Pedometer[33,41] or the Six minute Walk Test in different environments[43], due to incorrect statistical methods. The quality of the statistical outcomes in terms of measurement error was negative for all studies. None of the studies reported a minimal important difference or minimal important change based on the smallest important subjective difference to stroke survivors.[46-48] Only Kollen et al.[46] mentioned a minimal important change of 10% based on the perspective of health care practitioners.

Walking distance (d4500). Reported tests assessing walking distance were the Two minute Walk Test (2minWT[30]), Six minute Walk Test (6minWT[10,27,30,37,38,49]) and Twelve minute Walk Test (12minWT[27,30]).

The 6minWT[10,27,37,38,49] and 12minWT[27,30] demonstrated good test-retest reliability and concurrent validity. However, a poor interrater reliability was found for the 12minWT[30] (Table 2.5). No data were available for the 2minWT.

Walking speed (d4500). Reported tests assessing walking speed were the Four metre Comfortable Walk Test (4mCWT[27]), Five metre Walk Test unspecified (5mWT[50]), Five metre Comfortable Walk Test (5mCWT[28,45,46,51,52]), Five metre Fast Walk Test (5mFWT[45]), Six metre Comfortable Walk Test (6mCWT[53]), Ten metre Comfortable Walk Test (10mCWT[31,37,39,40,45]), Ten metre Fast Walk Test (10mFWT[4,37,39,45]), Ten metre Walk Turn Test (10mWTT[26,28,29]), Thirty metre Comfortable Walk Test (30mCWT[40]), Footswitch System (FS[32,35,54]), Accelerometer (AM[41,42]) and Pedometer (PM[33,41]).

Good reliability was reported for the 5mCWT[52], 6mCWT[53], 10mCWT[31,37], 10mFWT[31,37], 10mWTT[29] and FS[35,54]. Good concurrent validity was indicated for the 4mCWT[27], 5mWT[50], 6mCWT[53], 10mCWT[39,40], 30mCWT[40], FS[32] and AM[42] (Table 2.5). Poor concurrent validity was reported between the 10mCWT and self-assessment of walking ability.[40]

Table 2.4. Description of study population and methodological design

Walking test	Study population				Methodological design of the study[c]					
	N	Mean age ±SD	Stroke phase[a]	Specific selection criteria or characteristics[b]	Rep.	Rest between rep. on 1 day	Time between testing days	Testing period	No. of raters	Walkway
2minWT[30]	18	77±11	≤ Chronic		7		≥1 day	4 weeks	2	122 m rectangular
6minWT[37]	50	58±6	Chronic	≥300 m walking ability; I- and HCVA	2			1 week	1	30 m
6minWT[10]	37	66±14	≤ Post-acute	≥15 m walking ability; ≤1 person assist; first ever stroke	2		1–3 days	1–3 days	>1	46 m at 1 location; 76 m at the other 2
6minWT[30]	18	77±11	≤ Chronic		7		≥1 day	4 weeks	2	122 m rectangular
6minWT[49]	83	72±10	≥ Post-acute	Completed rehab; walking deficits	2	30 min		1 day		20 m
6minWT[27]	25	63±9	Chronic		1			1 day		42 m rectangular
6minWT[38]	12	63±9	Chronic	Ability to perform a cycle test	2		≥1 day	?		42 m rectangular
12minWT[30]	18	77±11	≤ Chronic		7		≥1 day	4 weeks	2	122 m rectangular
12minWT[27]	25	63±9	Chronic		1			1 day		42 m rectangular
4mCWT[27]	25	63±9	Chronic		1			1 day		8 m
5mWT[50]	35	66±13	≥ Sub-acute	First ever stroke	3			1 day		
5mCWT[51]	61	65±13	?	No walking frame; ≤1 person assist	2			56±38 days		10 m
5mCWT[52]	35	67±14	≤ Post-acute	≤1 person assist	2x >1	?	1–3 days	1–3 days	6	9 m
5mCWT[45]	50	68±13	Acute + sub-acute	First ever stroke; ≥14 m walking ability; ambulatory by 3 weeks	2			4 weeks	2	9 m
5mCWT[28]	21	72±?	Chronic		2x 3	?	≥1 week	3 weeks	2	5 m at home
5mFWT[45]	50	68±13	Acute + sub-acute	First ever stroke; ≥14 m walking ability; ambulatory by 3 weeks	2			4 weeks	2	9 m
6mCWT[53]	45	68±11	≤ Post-acute		2x 2	10 min	1 day	2 day	2	10 m
10mCWT[37]	50	58±6	Chronic	≥300 m walking ability; I- and HCVA	2x 3	30 sec		1 week	1	14 m linoleum
10mCWT[45]	50	68±13	Acute + sub-acute	First ever stroke; ≥14 m walking ability; ambulatory by 3 weeks	2			4 weeks	2	9 or 14 m
10mCWT[39]	28	65±13	Chronic	≤2 falls ≤6 months; walking in community ≥1 per week	3			1 day		14 m
10mCWT[31]	12	67±15	Acute + sub-acute		3			1 day	2	10 m
10mCWT[40]	18	54±?	Chronic	Rehab completed for ≥3 months	4	2 min		1 day	1	30 m
10mFWT[37]	50	58±6	Chronic	≥300 m walking ability; I- and HCVA	2x 3	30 sec		1 week	1	14 m linoleum
10mFWT[45]	50	68±13	Acute + sub-acute	First ever stroke; ≥14 m walking ability; ambulatory by 3 weeks	2			4 weeks	2	9 or 14 m
10mFWT[31]	12	67±15	Acute + sub-acute		3			1 day	2	10 m
10mFWT[4]	40	70±9	Chronic	Ataxia and impaired balance were excluded	2x 2	1 min		1 year		11 m
10mWTT[29]	20	72±7	Chronic	No physical therapy for ≤6 months	2x 3		≥7 days	≤17 days	1	5 m
10mWTT[26]	43	66±11	≥ Post-acute	4x 10 m walking ability	2			1 day	5	5 m
10mWTT[28]	21	72±?	Chronic		2x 3	?	≥1 week	3 weeks	2	5 m at home

Walking test	Study population				Methodological design of the study[c]					
	N	Mean age ±SD	Stroke phase[a]	Specific selection criteria or characteristics[b]	Rep.	Rest between rep. on 1 day	Time between testing days	Testing period	No. of raters	Walkway
30mCWT[40]	18	54±?	Chronic	Rehab completed for ≥3 months	4	2 min		1 day	1	30 m
FS[54]	31	69±?	Sub-acute + post-acute	Only cerebral strokes	4 (1x 2)	10 min	1 day	3 days		10 m (6 m course)
FS[32]	25	56±16	≥ Post-acute		?			?		25 m (15 m course)
FS[35]	22	73±10	Post-acute	First ever stroke; ≥10 m walking ability; no walking devices	≥2	5 min		1 day		10 m (6 m course)
AM[41]	16	67±7	Chronic	ICVA; completed rehab; gait deficits present	2x 3	?	>1 day	?		
AM[42]	25	69±?	Chronic	Independent walk; no botox ≤1 year; ≤2 falls ≤6 months	9			?		Different
PM[33]	20	54±13	Chronic	≥2 min walking ability	1			1 day		16 m
PM[41]	16	67±7	Chronic	ICVA; completed rehab; present gait deficits	2x 3	?	>1 day	?		
6minWTDE[43]	30	61±11	Chronic	≥6 min walking ability; no walking frame; gait speed 20-50 m/min	1x 3	≥5 min		1 day		Different for every environment
300mWT[39]	28	65±13	Chronic	≤2 falls ≤6 months; walking in community ≥1 per week	1			1 day		300 m community-based circuit
FAC 3-5[46]	73	65±11	≥ Acute	First ever ICVA; no use of walker	16		≥1 week	26 weeks	1	
FAC[34]	55	63±10	Post-acute	First ever I- or HCVA; week 0 unable to walk (independently)	4		≥1 week	24 weeks	4	
FAC[31]	24	68±12	Acute + sub-acute	Independent stand	2			1 day	2	
FAC[28]	25	72±?	Chronic		3		≥1 week	≥4 weeks		
FACHS[44]	31	64±8	≤ Chronic		3			1 day	3	
DGI[55]	25	62±13	Chronic	First ever stroke; co-morbidities included	2		3 days	3 days	2	
DGI[36]	45	60±13	≥ Post-acute	First ever I- or HCVA	3		≥2 months	5 months	1	
DGI-4[36]	45	60±13	≥ Post-acute	First ever I- or HCVA	3		≥2 months	5 months	1	
FGA[56]	28	70±10	≤ Chronic	First ever I- or HCVA; ≥15 m walking ability	2			≥1 months	3	
FGA[36]	45	60±13	≥ Post-acute	First ever I- or HCVA	3		≥2 months	5 months	1	
6mWTPC[57]	24	62±?	≥ Post-acute	First ever I- or HCVA	2x 2	5 min	1 day	2 days	1	10 m

Abbreviations of the walking tests are shown in Table 2.3.
N, number of participants; SD, standard deviation; Rep, repetitions; wk0, baseline; min, minute(s); sec, second(s); m, metre(s); mm, millimetre; x, series; ICVA, ischemic stroke; HCVA, haemorrhagic stroke; ?, important information not available; *open cell,* no information available.
[a] Phase of stroke: acute (1st week), sub-acute (2nd – 4th week), post-acute (2nd – 6th month) and chronic (>6 months).
[b] All studies excluded participants on: co-morbidities which involve walking ability, inability to walk 10 m and severe deficits in communication, perception and cognition except when mentioned in this table. In almost all studies, participants had to walk independently, which means without physical assistance (walking devices allowed) except when mentioned in this table.

Table 2.5. Evaluation of the methodological design, statistical methods and statistical outcomes of the walking capacity measurements, by study

Walking test	Reliability				Measurement error			Validity[b]					Responsiveness			Statistics
	Test-retest or rater reliability	MD	SM	SO	MD	SM	Calculated outcomes[a]	Type of validity	MD	SM	SO	Compared to	MD	SM	SO	Actual values[c]
2minWT[30]	Inter-rater	0	+	+												ICC .85
	Intra-rater			+												ICC .85
6minWT[37]	Test-retest	++	+	+	++	+	SEM 18.6 m									ICC .99 (CI .98-.99)
6minWT[10]	Test-retest	++	+	+	++	+	SEM 23.2 m, MDC_{90} 54.1 m	Concurrent	+++	+	+	5MCWT,				ICC .97 (CI .93-.99)
											-	FIM locomotion and				r_p .89*, r_s .69* and
											-	FIM locomotion + stairs				r_s .69
6minWT[30]	Inter-rater	0	+	+												ICC .78
	Intra-rater			+												ICC .74
6minWT[49]	Test-retest	++	+	+	++	+	LoA cannot be interpreted									ICC .98 (CI .97-.99)
6minWT[27]								Concurrent	+	+	+	12MWT distance				r_p .97*
											+	4MCWT				r_p .92*
6minWT[38]	Test-retest	+	+	+	+	+	SEM 12.4 m									ICC .99
12minWT[30]	Inter-rater	+	+	-									++	0		ICC .68
	Intra-rater			+												ICC .71
12minWT[27]								Concurrent	+	+	+	6MWT distance				r_p .97*
											+	4MCWT				r_p .91*
4mCWT[27]								Concurrent			+	6MWT				r_p .92*
									+	+	+	12MWT distance				r_p .91*
5mWT[50]					+	0										
5mCWT[51]													+	0		
5mCWT[52]	Test-retest	++	+	+	++	+	MDC_{90} .3 m/s						+	0		ICC .86 (CI .68-.94)
5mCWT[45]													+	0		
5mCWT[28]	Test-retest	++	0													
5mFWT[45]													+	0		
6mCWT[53]	Inter-rater	++	+	+				Concurrent	+++	+	+	10MCWT				ICCs .99
	Intra-rater			+												r_s .99*
10mCWT[37]	Test-retest	++	+	+	++	+	SEM .07 m/s									ICC .94 (CI .90-.97)
10mCWT[45]													++	0		
10mCWT[31]	Inter-rater	++	+	+	+	+	LoA -.72 to .78 s									ICC 1.00
10mCWT[39]								Concurrent	+	+	+	*Neg* 300MWT				r_s -.88*
10mCWT[40]								Concurrent	+	+	+	*Neg* no. of steps				r_s -.97*
											-	Self-assessment of walking ability				r_s .50*
10mFWT[37]	Test-retest	++	+	+	++	+	SEM .08 m/s									ICC .97 (CI .95-.98)
10mFWT[45]													+	0		

Walking test	Reliability				Measurement error			Validity[b]					Responsiveness			Statistics
	Test-retest or rater reliability	MD	SM	SO	MD	SM	Calculated outcomes[a]	Type of validity	MD	SM	SO	Compared to	MD	SM	SO	Actual values[c]
10mFWT[31]	Inter-rater	++	+	+	++	+	LoA -.4 to .44 s									ICC 1.00
10mFWT[4]	Test-retest	+	0													
10mWTT[29]	Test-retest	++	+	+	++	+	LoA varied from -10.92 to 9.12 s									ICC .87 (CI .72-.95)
10mWTT[26]								Concurrent	+	+	-	10MCWT				r_p .69*
10mWTT[28]	Test-retest	++	0													
30mCWT[40]								Concurrent	+	+	+	*Neg* 10mCWT				r_s -.91*
FS[54]	Test-retest (intra- and intersession)	+	+	+	+	+	SEMC gait speed 4.31 and 4.37 m/min SEMC cadence 7.45 and 6.16 steps/min (intra vs. inter)									ICC .94 ICC .92
FS[32]								Concurrent	+	+	+	Velocity and cadence compared to the FAC				r_s .73* r_s .70*
FS[35]	Test-retest (velocity and cadance)	++	+	+	++	+	SEM gait speed 3.33 m/min, SEM cadence 7.98 steps/min									ICC .95 ICC .92
AM[41]	Test-retest	+	0					Concurrent (gold)	+	0		Elexis Trainer #FM-180				
AM[42]								Concurrent	+	+	+	3 dimensional gait analysis indoor				r_p .87-.96
											+	FS outdoor				r_p .96-.99
PM[33]					+	0		Concurrent (gold)	+	0		Manual Step Counter				
PM[41]	Test-retest	+	0					Concurrent (gold)	+	0		Step Activity Monitor				
6minWTDE[43]								Concurrent	+	0		10MWT 6MWT				
300mWT[39]								Concurrent	+	+	+	*Neg* 10MCWT				r_s -.88*
FAC 3-5[46]													+	0		
FAC[34]	Test-retest	+	+	+				Concurrent	+	+	+	6MWT	+	+	+	K .85 and K .91
	Inter-rater			+							+	10MFWT				r_s .91-.95* and r_s .90-.95* 67-100% sensitivity 16-100% specificity
FAC[31]	Inter-rater	++	0													

Table 2.5 continues on the next page.

Table 2.5. *Continued*

Walking test	Reliability				Measurement error			Validity[b]					Responsiveness			Statistics
	Test-retest or rater reliability	MD	SM	SO	MD	SM	Calculated outcomes[a]	Type of validity	MD	SM	SO	Compared to	MD	SM	SO	Actual values[c]
FAC[28] FACHS[44]	Test-retest	++	+	- 				Concurrent	+	+	+ +	Different walking speeds and steps				K .36 r_s .74-.84* r_s .86*
DGI[55]	Test-retest Inter-rater	++	+	+ +	++	+	Test-retest LoA -.03 SD 1.07; inter-rater LoA .42 SD 1.33	Hypotheses testing	+	+	+	*Neg* 10MCWT				ICC .96 (CI .90-.98) ICC .96 (CI .83-.98) r_s -.77*
DGI[36]	Test-retest	++	+	+	++	+	MDC_{95} 4.0	Concurrent	++	+	+ - +	DGI-4 and FGA *Neg* 10MCWT 0wk, 10MCWT 8 and 25wk	+	0		ICC .94 (CI .90-.97) r_s >.91*, r_s -.68*, r_s -.87* and r_s -.83*
DGI-4[36]	Test-retest	++	+	+	++	+	MDC_{95} 2.3	Concurrent	++	+	+ - +	DGI and FGA *Neg* 10MCWT 0wk, 10MCWT 8 and 25wk	+	0		ICC .92 (CI .87-.96) r_s >.91*, r_s -.61*, r_s -.77* and r_s -.74*
FGA[56]	Inter-rater Intra-rater	+	+	+ +				Concurrent	+	+	+ +	FAC 10MFWT				ICC .94 (CI .89-.97) ICC .97 (CI .95-.98) r_s .83* and r_s .82*
FGA[36]	Test-retest	++	+	+	++	+	MDC_{95} 4.2	Concurrent	++	+	+ - +	DGI and DGI-4 *Neg* 10MCWT 0wk, 10MCWT 8 and 25wk	+	0		ICC .95 (CI .91-.97) r_s >.91*, r_s -.66*, r_s -.85* and r_s -.81*
6mWTPC[57]	Test-retest	+	+	+	+	0		Predictive	+	+	+	Comfortable/fast walk and parquetry/carpet compared				ICC .94-.97; Comfortable walk r_p .92 Fast walk r_p .97

Abbreviations of the walking tests are shown in Table 2.3. MD, Methodological design; SM, Statistical method; SO, Statistical outcomes; +, positive element of the measurement evaluation; 0 or -, negative element of the measurement evaluation; *open cell*, no information available; FIM, Functional Independence Measure; wk, week(s); LoA, limits of agreement; SEM, standard error of measurement; SEMC, standard error of measuring change; MDC, minimal detectable change; m, metre(s); s, second(s); min, minute(s); ICC, interclass correlation coefficient (and 95% confidence interval); K, Kappa; r_p, Pearson correlation coefficient; r_s, Spearman correlation coefficient.

[a] When no percentage is given, it was set at 95%.

[b] Construct validity is subdivided into structural validity, hypothesis testing and cross-cultural validity. Criterion validity is subdivided into concurrent (to gold standard or alternative) and predictive validity. Gold standards are indicated in the table. *Neg*, negative significant correlation (p<.05).

[c] The statistic results in the studies for reliability, validity and responsiveness.

* p<.05.

Functional ambulation (d4500). Reported tests assessing functional ambulation were the Six minute Walk Test in different environments (6minWTDE[43]), Three hundred metre Walk Test in the community (300mWT[39]), Functional Ambulation Categories (FAC[28,31,34,46]), Functional Ambulation Classification Hospital Sagunto (FACHS[44]), Dynamic Gait Index (DGI[36,55]), Dynamic Gait Index 4 items (DGI-4[36]) and Functional Gait Assessment (FGA[36,56]).

Good reliability was indicated for the FAC[34], DGI[36,55], DGI-4[36] and FGA[36,56]. There was a discrepancy regarding the test-retest reliability of the FAC. Collen et al.[28] suggested poor test-retest reliability, whereas Mehrholz et al.[34] suggested good test-retest reliability. Responsiveness outcomes of the FAC[34] demonstrated a sensitivity of between 67 and 100%, and a specificity of between 16 and 100%. Good validity was reported for the 300mWT[39], FAC[34], FACHS[29], DGI[36,55], DGI-4[36] and FGA[36,56]. Discrepancies were found for the concurrent validity of the DGI, DGI-4 and FGA compared with the 10MCWT[36]. Correlations when compared with the 10MCWT were poor at baseline but good after 2 and 5 months of outpatient rehabilitation.[36] No floor or ceiling effects were found for the DGI[36,55] and FGA[36], although a ceiling effect was found for the DGI-4[36] (Table 2.5).

Walking on different surfaces (d4502). The only reported test assessing walking on different surfaces was the Six metre Walk Test on parquet and carpet (6mWTPC[57]).

Good reliability and good predictive criterion validity, for prediction of walking speed on carpet by assessing walking speed on parquetry, were indicated for the 6mWTPC[57] (Table 2.5).

Discussion

The present systematic review offers clinicians and researchers an extensive overview of 23 walking tests, categorised according to the ICF classification, which have been evaluated among stroke survivors in terms of measurement properties. Thirty-two studies evaluated 23 walking tests assessing “short walking distance”, “walking speed”, “functional ambulation” and “walking on different surfaces”. The Six minute Walk Test, Ten metre Comfortable Walk Test, Ten metre Fast Walk Test, Functional Ambulation Categories and Six metre Walk Test on parquet and carpet are most studied and show to be valid, reliable and feasible for stroke survivors. Although good reliability and validity, according to the cut-off values (Table 2.2), were found for most tests, data on responsiveness and measurement error are still lacking. Depending on the specific measurement aim (for example walking distance) clinicians and researchers could use this review as a helpful resource in choosing a valid and reliable walking test for their stroke patients (Table 2.5).

It is important for clinicians and researchers to standardize and clearly report testing procedures, since this improves interpretability, reliability and responsiveness of tests.[49,58] The measurement protocols described in the included studies vary with differences being

reported in walking distances, walking speeds, encouragement, walking devices and physical assistance. The protocols for the timed walking tests differed in terms of the distance before starting (acceleration) and after stopping (deceleration) the measurement (0–3 m), and in terms of instructions for walking speed (slow, comfortable, preferred/self-selected or maximum). Encouragement was not standardized, despite the positive impact of encouragement on measurement results of walking tests that could negatively influence reliability and responsiveness.[49,58] Also, the use of walking devices and frequency of using walking devices was not always reported in the included studies, although the use of a walking device or physical assistance can improve the measurement outcome.[10,40] Some of the studies mentioned "independent walking", but it is not clear if they mean walking without walking devices and/or physical assistance.[42,59] These issues highlight the importance of standardization and detailed reporting of test situations which improves quality of testing.

Methodological strengths of the present review are the use of the COSMIN checklist and the use of a quality assessment for the statistical outcomes. The COSMIN checklist is an instrument to determine the quality of methodological design and statistical methods of clinimetric studies.[18-20] The checklist encompasses all measurement properties, is based on recent literature, and is, in our opinion, currently the best available instrument to evaluate clinimetric studies. Although the COSMIN checklist was developed for evaluation of patient-reported measurement tools and not performance-based tests, our experience is that the items are also relevant for performance-based tests after minor modification.

The use of a quality assessment for statistical outcomes provides an overview without the necessity to interpret all statistical outcomes. In the present review, a new quality assessment was used, based on the quality assessments developed by Schellingerhout et al.[24] and Van der Leeden et al.[25]. Where Schellingerhout et al.[24] and Van der Leeden et al.[25] combined the assessment of statistical methods and statistical outcomes into one quality assessment, the new quality assessment separates these which provides the reader with more detail about the studies' quality and outcomes. Moreover, no grading of the quality (e.g. 1–3) was used because of the questionable statistical cut-off points, and our quality assessment described all the measurement properties, in contrast to those by Schellingerhout et al.[24] and Van der Leeden et al.[25].

It could be discussed that the present review is limited by inclusion of only clinimetric studies. The reason for excluding studies that do not evaluate measurement properties as primary aim, is the little information on protocols of the walking tests and the limited description of the methodology. A second limitation is that not all databases (e.g. AMED, PEDro) have been searched. However, the most important databases were searched and reference lists of retrieved articles were also checked, missing relevant studies is not expected. Validity of the described walking tests was only studied in relation to other walking tests and not against, for example mobility outcomes. The scope of this study was evaluation of measures of walking ability only. Therefore mobility related activities,

like transfers, were left out. Another point of discussion is the disputability in which ICF component a walking test should be categorised, as some walking tests include elements of more than one ICF component (e.g. the Six minute Walk Test in different environments). We categorized the walking components as measured by the walking tests into the ICF category it was, in our opinion, strongest related with. However, we are aware that some walking tests could also be classified in other ICF categories of walking.

Although we see the use of the COSMIN checklist as a valuable and thorough assessment of clinimetric studies, there are some related limitations to the use of this checklist. Good training is recommended prior to the use of the COSMIN checklist to improve levels of consistency between reviewers. The level of consistency between the two reviewers prior to discussion was moderate (κ=0.51) for this review. This is consistent with a previous study by the COSMIN panel (61% was κ<0.40, 6% was κ>0.75).[60] The COSMIN checklist sets high standards for methodological design of clinimetric studies and reporting. Where Jonsdottir and Cattaneo[55] provided hypotheses to evaluate construct validity and used the correct statistical methods (i.e. correlations) for evaluation, all other included studies failed to do so. The methodological quality in terms of construct validity would often be rated as “poor” quality, since three out of seven COSMIN items concern hypotheses. To overcome the problem of valuable information being missing, construct validity was divided in the present review into structural validity, hypothesis testing, cross-cultural validity and besides those types of validity also concurrent validity without a golden standard.

In agreement with the COSMIN panel, we recommend future research to report hypotheses, including their magnitude and direction, in the evaluation of hypothesis testing as a component of construct validity.[18,19] Furthermore, future clinimetric studies should use the COSMIN checklist and a quality assessment like Table 2.2, to improve the methodological and statistical design and reporting. A limitation of the studies included in the present review is the lack of information on their design and, consequently, on the items of the COSMIN checklist. Information about the COSMIN items of “missing data” (the percentage of missing data), “adequate sample size” (sample size calculation or n≥50) and “independent administrations” (assessors blinded) was often absent resulting in lower methodological design scores due to underreporting. Moreover, statistical analyses of some studies were rated as incorrect, according to recent views for reporting measurement properties.[20] Future research on measurement properties of walking tests should report not only reliability but also measurement error. Although statistical outcomes like the standard error of measurement, limits of agreement or smallest detectable difference were frequently reported, it is recommended to present this information in relation to minimal important difference or minimal important change.[47,48,61] Moreover, responsiveness is an important aspect of a measure’s validity and needs further study, since this information is lacking.

In conclusion, many walking tests are available to assess walking ability in stroke

survivors. Most walking tests in the present systematic review were found to be reliable and valid, but important clinimetric information such as responsiveness and minimal important change is still missing. Clinicians and researchers can use this review as a helpful resource for choosing a valid and reliable walking test which suits the aim of the assessment.

Implications for rehabilitation

- Many tests assessing walking in stroke survivors are available in the literature. The Six Minute Walk Test, Ten Metre Comfortable Walk Test, Ten Metre Fast Walk Test, Functional Ambulation Categories and Six Metre Walk Test on parquet and carpet have been most frequently clinimetrically evaluated. These tests amongst others, have been shown to be valid, reliable and feasible for stroke survivors.
- With the wide variety of walking tests, it is important to choose an appropriate walking test suiting the specific aim of the clinician or researcher.

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Supplement 2.1.

Search Strategy PubMed.

#1 (P): ("stroke"[MeSH] OR stroke[tiab] OR "cerebrovascular accident"[tiab] OR "brain vascular accident"[tiab] OR "cerebrovascular disorders"[tiab] OR CVA*[tiab] OR cerebrovasc*[tiab] OR "cerebral vascular"[tiab] OR cerebrovascular[tiab] OR hemipleg*[tiab] OR hemipar*[tiab] OR ((cerebral[tiab] OR cerebellar[tiab] OR brain*[tiab] OR vertebrobasilar[tiab]) AND (infarct*[tiab] OR ischemi*[tiab] OR thrombosis[tiab] OR emboli*[tiab] OR apoplexy[tiab])) OR ((cerebral[tiab] OR brain*[tiab] OR subarachnoid[tiab] OR intracerebral[tiab] OR intracranial[tiab] OR parenchymal[tiab] OR intraventricular[tiab] OR periventricular[tiab] OR cerebellar[tiab] OR infratentorial[tiab] OR supratentorial[tiab]) AND (haemorrhage[tiab] OR hemorrhage[tiab] OR haematoma[tiab] OR hematoma[tiab] OR bleed*[tiab] OR aneurysm[tiab])) NOT "cerebral palsy")

#2 (I): ("gait"[MeSH] OR gait[tiab] OR walk*[tiab] OR "walking"[MeSH] OR walking[tiab] OR ambulation[tiab] OR mobility[tiab] OR ((minute*[tiab] OR meter*[tiab]) AND walk*[tiab]))

#3 (I): (test[tiab] OR tests[tiab] OR instrument*[tiab] OR (performance-based[tiab] AND method*[tiab]) OR measur*[tiab] OR ((performance[tiab] OR observational[tiab]) AND (index[tiab] OR indices[tiab])) OR assessment*[tiab] OR (objective[tiab] AND method*[tiab]) OR "objective evaluation"[tiab] OR (objective[tiab] AND function*[tiab]) OR "objective disability"[tiab] OR (subjective[tiab] AND method*[tiab]) OR "subjective evaluation"[tiab] OR (subjective[tiab] AND function*[tiab]) OR "subjective disability"[tiab] OR (observational[tiab] AND method*[tiab]) OR (observation-based[tiab] AND method*[tiab]) OR "observed disability"[tiab] OR (observed[tiab] AND function*[tiab]) OR scale*[tiab] OR questionnair*[tiab] OR exam*[tiab] OR investigat*[tiab] OR "outcome assessment (health care)"[MeSH] OR "outcome assessment"[tiab])

#4 (O): ("validation studies"[pt] OR "reproducibility of results"[MeSH] OR reproducibility[tiab] OR reproducib*[title] OR "measurements"[MeSH] OR psychometr*[title] OR clinimetr*[title] OR clinometr*[title] OR "observer variation"[MeSH] OR observer variation[title] OR reliability[tiab] OR reliab*[title] OR validity[tiab] OR validation[tiab] OR valid*[title] OR ((generaliza*[tiab] OR generalisa*[tiab] OR reliab*[tiab] OR "intraclass correlation"[tiab]) AND coefficient*[tiab]) OR "internal consistency"[tiab] OR (cronbach*[tiab] AND (alpha[tiab] OR alphas[tiab])) OR (item[tiab] AND (correlation*[tiab] OR selection*[tiab] OR reduction*[tiab])) OR agreement[tiab] OR precision[title] OR imprecision[title] OR test-retest[tiab] OR (test[tiab] AND retest[tiab]) OR (reliab*[tiab] AND (test[tiab] OR retest[tiab])) OR ((interrater[tiab] OR inter-rater[tiab] OR intrarater[tiab] OR intra-rater[tiab]

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#5: #1 AND #2 AND #3 AND #4

#6: #5 NOT ("review"[pt] OR "addresses"[pt] OR "biography"[pt] OR "case reports"[pt] OR "comment"[pt] OR "directory"[pt] OR "editorial"[pt] OR "festschrift"[pt] OR "interview"[pt] OR "lectures"[pt] OR "legal cases"[pt] OR "legislation"[pt] OR "letter"[pt] OR "news"[pt] OR "newspaper article"[pt] OR "patient education handout"[pt] OR "popular works"[pt] OR "congresses"[pt] OR "consensus development conference"[pt] OR "consensus development conference, nih"[pt] OR "practice guideline"[pt]) NOT ("animals"[MeSH] NOT "humans"[MeSH])

Chapter 3

The Shuttle Walk Test: a new approach to functional walking capacity measurements for patients after stroke?

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Astrid M. Kokkeler
Ingrid G.L. van de Port

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Abstract

Objective. To determine the construct validity, test-retest reliability, and measurement error of the shuttle walk test (SWT) for patients after stroke.

Design. Clinimetric study.

Setting. Three rehabilitation centers in the Netherlands.

Participants. A sample of patients after stroke (n=75; mean age ± SD, 58.8±9.8 y) who are capable of walking without physical assistance. Patients were excluded if they had sustained a subarachnoid hemorrhage or a stroke in the cerebellum or brainstem, or had any other conditions that limited their walking capacity more than the current stroke, or had sensory aphasia.

Interventions. Not applicable.

Main outcome measures. Construct validity (6-minute walk test [6MWT]) and test-retest reliability of the SWT were assessed. Measurement error was determined with the standard error of measurement (SEM), limits of agreement, and smallest detectable differences (SDDs).

Results. Construct validity was confirmed by high significant correlations ($r_p \geq .65$, $p < .01$) between the SWT and 6MWT. Difference scores were significantly higher in favor of the SWT for high-speed walkers (≥0.8m/s). In the small group (n=12) of low-speed walkers (<0.8m/s), no significant correlations and differences between both tests were found except for walking distance in favor of the 6MWT. Test-retest reliability was good (intraclass correlation coefficient model 2,1 [$ICC_{2,1}$]=.961 [.936–.977]). SEM was 6.0%, and the SDDs for individual and group were 302.0m (37%) and 38.7m (5%), respectively.

Conclusions. The SWT is a valid and reliable measure and therefore a feasible instrument to determine functional walking capacity of patients after stroke, especially in high-speed walkers.

Introduction

Functional walking capacity has been defined as the extent to which a person can increase walking exercise intensities and maintain the increased levels.[1] The valid and reliable 6-minute walk test (6MWT) is one of the most frequently used functional walk tests in stroke rehabilitation, despite the lack of data on its responsiveness and minimal important change (MIC).[2-4] Despite the wide use, the 6MWT requires a long walking track, it can only be performed on an individual basis, and participants may be influenced by self-paced walking speed, motivation, and encouragement that cannot be standardized and might influence the level of exertion. An alternative test used in patients with chronic airway obstruction, and heart and lung diseases is the shuttle walk test (SWT) as originally described by Singh et al.[5]. Verschuren et al.[6] developed a modified SWT for children with cerebral palsy, which, compared with the original SWT, uses smaller increments in walking speed over the 10-m course. This protocol might be a more suitable functional walk test for individuals with motor deficits, including patients after stroke.

The purpose of this study was to examine the measurement properties of the SWT in patients after stroke. The properties determined included construct validity, as assessed by correlations with the 6MWT, test-retest reliability, and measurement error.

Methods

Patients after stroke who received rehabilitation between January and April 2010 in 1 of 3 rehabilitation centers in the Netherlands were asked to participate. In addition, a convenience sample of discharged patients was recruited from the 2006 through 2009 database of 1 rehabilitation center. Inclusion criteria were (1) stroke verified by a physician; (2) age between 18 and 80 years; (3) walking without physical assistance; and (4) understanding simple instructions. Exclusion criteria were (1) a subarachnoid hemorrhage, stroke in the cerebellum or brainstem; (2) limited walking capacity caused by other conditions than the current stroke; or (3) sensory aphasia. The Medical Ethics Committee of the University Medical Center Utrecht and all medical ethics committees of the participating rehabilitation centers approved the study. All 75 participants provided informed consent. Data were collected by 2 experienced physiotherapists (M.B. and A.K.). Test-retest reliability of the SWT was assessed over a 2- to 8-day interval. If the time elapsed since the stroke was less than 12 weeks, the second SWT measurement was not carried out because of the possible recovery during this stage after stroke. During the first measurement, both the SWT and the 6MWT were performed, in alternating order, with at least 2 hours in between.

Outcome measures

Shuttle walk test. The 10-m SWT was conducted according to the protocol by Verschuren,[6] except in the present study 2 cones were placed 9m apart, to turn around and avoid abrupt changes of direction. The SWT consists of 23 stages, each lasting approximately 1 minute. In each stage, the speed is increased by .25km/h, with an initial speed of 2.0km/h rising to a maximum speed of 7.5km/h. The beginning and end of each stage are indicated by an auditory signal (beep). Participants were instructed to keep walking for as long as possible, not to talk during the test, and if they reached the cone before the beep, to wait until the beep had sounded. The first stage was demonstrated by the assessor. The test ended when the participant was unable to reach the next cone before the signal. The test was also stopped when safety was no longer ensured – for example, when the participant showed vital discomforts (eg, shortness of breath) or walking problems (eg, increased imbalance) that could lead to falling. Both assessors are experienced physiotherapist and discussed the stopping criteria before the start of the study. Encouragement was constantly offered by the assessor at the beginning of every stage. If possible, the SWT was performed in groups, with a maximum of 4 participants. To ensure the participants' safety and to indicate the walking speed for the participants, an assistant walked alongside the walkway. Before the start of the test, participants were fitted with a Polar heart rate (HR) monitor (Polar Electro Inc., NY, USA) to determine HR at rest (after they had sat in a chair for at least 5min) and immediately after the test. Rate of perceived exertion (RPE) was assessed by the Borg scale[7] (range, 6–20) at the beginning and immediately after the test.

Six minute walk test. The 6MWT was conducted as described by the American Thoracic Society,[8] requiring participants to walk over a 30-m course with 2 cones placed 0.5m from either end to avoid abrupt changes of direction. Participants were accompanied by 1 assessor who walked behind them, to ensure their safety during the test. HR and RPE were assessed in the same way as for the SWT procedure.

Statistical analysis

To assess construct validity, the following hypotheses were formulated: (1) the SWT shows significant positive correlations with the 6MWT for walking distance, peak HR (HR_{peak}), and RPE; and (2) there are significant differences in absolute walking distance, HR_{peak}, and RPE in favor of the SWT in patients after stroke with a high walking speed (≥0.8m/s), and in favor of the 6MWT in patients after stroke with a low walking speed (<0.8m/s). Pearson correlation coefficients were used, with a value of 0.5 or greater indicating good construct validity.[9] Differences between the SWT and 6MWT were determined using paired *t* tests. Test-retest reliability for walking distance on the SWT was examined using an intraclass correlation coefficient ($ICC_{2,1}$) and 95% confidence interval (CI). An $ICC_{2,1}$ of 0.7 or greater indicates good reliability.[10] Measurement error was reflected by the standard error of

measurement ($SEM_{agreement}$) and the 95% limits of agreement (LoA).[10] The $SEM_{agreement}$ was considered small if it represented less than 10% of the score range.[11] Since the MIC of the SWT is not available, the ratio between the smallest detectable difference (SDD) and SD was determined. The SDD was determined on an individual and a group level:

$$SDD_{individual} = 1.96 \cdot SEM_{agreement} \cdot \sqrt{2} \quad (1)$$

$$SDD_{group} = [1.96 \cdot SEM_{agreement} \cdot \sqrt{2}] / \sqrt{n} \quad (2)$$

An SDD/SD ratio above 0.8 was interpreted as requiring large score differences to exceed chance.[12] Significance was set at $p<.05$. Data analysis was performed using SPSS Version 16.0 (SPSS Inc., Chicago, IL, USA).

Results

Not all 75 participants (Table 3.1) were able to participate in both examinations (validity and reliability), because of the time poststroke (n=7), planning problems (n=14), or physical problems on the second measurement day (n=1).

Table 3.1. Participant characteristics

Characteristics	Total	Validity examination	Reliability examination
No. of participants	75	70	61
Sex (men / women)	47 / 28	45 / 25	36 / 25
Age (y)	58.8±9.8	58.7±9.9	58.9±9.4
BMI	27.1±4.3	27.2±4.3	27.2±4.9
Time poststroke (mo)	24.7±25.3	23.9±24.6	27.7±26.4
Type of stroke (ICVA / HCVA)	57 / 18	53 / 17	47 / 14
Side of lesion (left / right)	32 / 43	31 / 39	27 / 34
Orthotics used at test (yes / no)	19 / 56	16 / 54	16 / 45
Walking devices used at test (yes / no)	19 / 56	17 / 53	15 / 46

NOTE. Values are n, mean ± SD, or as otherwise indicated. Abbreviations: BMI, body mass index; HCVA, hemorrhagic stroke; ICVA, ischemic stroke.

Construct validity of SWT and 6MWT

Correlation coefficients were large and significant (Table 3.2). A subgroup analysis was performed to verify the second hypothesis about the low- and high-speed walkers. Significant correlations for walking distance, HR_{peak}, and RPE were found between the 6MWT and SWT for the high-speed walkers (n=58), with differences in favor of the SWT. In the low-speed group (n=12), no significant correlations or differences were found between the 6MWT and SWT, except for walking distance in favor of the 6MWT.

Test-retest reliability and measurement error of SWT

Test-retest reliability was good ($ICC_{2,1}$=.961; 95% CI, .936–.977). The $SEM_{agreement}$ was 109.0m, reflecting 6.0% of the total range. The LoA were -272.3 and 327.0m (Figure 3.1).

The SDDs for individual and group were 302.0m (37%) and 38.7m (5% of the total range), respectively. The $SDD_{individual}$/SD ratio was 0.5, and the SDD_{group}/SD ratio was 0.1. Exclusion of the 2 outliers (judged visually; see Figure 3.1) did not change the results substantially.

Discussion

The SWT is a reliable test to measure functional walking capacity of patients after stroke. Both hypotheses on construct validity were confirmed, and the measurement error and SDD/SD ratio were within the boundaries described in literature. Even though the 6MWT has some disadvantages, the 6MWT was used to determine construct validity because it is the most frequently used instrument in research and clinical practice. No systematic differences were found between the repeated tests, indicating that there was no learning effect of the SWT. When using the SWT in clinical practice, one should consider the reported measurement error, which indicates that individuals still need to walk an additional 37% of the absolute distance to overcome any measurement error and show real clinical differences. The literature on the 6MWT is equivocal about the level of improvement required to show a real clinical difference. Differences ranging from 13% to 46% have been reported, and similar to the SWT, no MIC is known.[3] It remains unclear how useful the SWT is for determining the functional walking capacity of patients after stroke with a walking speed below 0.8m/s, since the sample size of low-speed walkers was small (n=12). Also, because the SWT seems to be a more demanding test than the 6MWT, it would be interesting to compare the peak oxygen uptake during the SWT with that during a standardized graded exercise test to establish a patient's exercise capacity.

Table 3.2. Subgroup analysis of construct validity

	Total group (n=70)			Subgroup: Walking speed <.8 m/s (n=12)				Subgroup: Walking speed ≥.8 m/s (n=58)			
	SWT	6MWT	r_p	SWT	6MWT	r_p	p^*	SWT	6MWT	r_p	p^*
Distance (m)	878.9±586.8	472.5±156.1	.928†	96.7±67.9	222.3±52.0	.734‡	.002	1044.2±514.1	521.9±115.4	.904†	.000
HR difference (bpm)	57.9±29.0	44.6±18.3	.755†§	25.7±11.9	27.4±12.4	.457	.432	64.6±27.0	48.2±17.4	.708†‖	.000‖
RPE difference	5.3±3.0	3.8±2.7	.646†§	3.0±2.5	2.2±3.2	.448	.277	5.8±2.9	4.1±2.5	.655†‖	.000‖

NOTE. Values are mean ± SD or as otherwise indicated. Difference is the difference between start and end of the test; distance is the walking distance in meters.
Abbreviations: bpm, beats per minute; r_p, Pearson correlation coefficient. *Significance of difference between SWT and 6MWT (paired *t* test).
†$p<.01$ (2-tailed); ‡$p<.05$ (2-tailed). §n=69. ‖n=57.

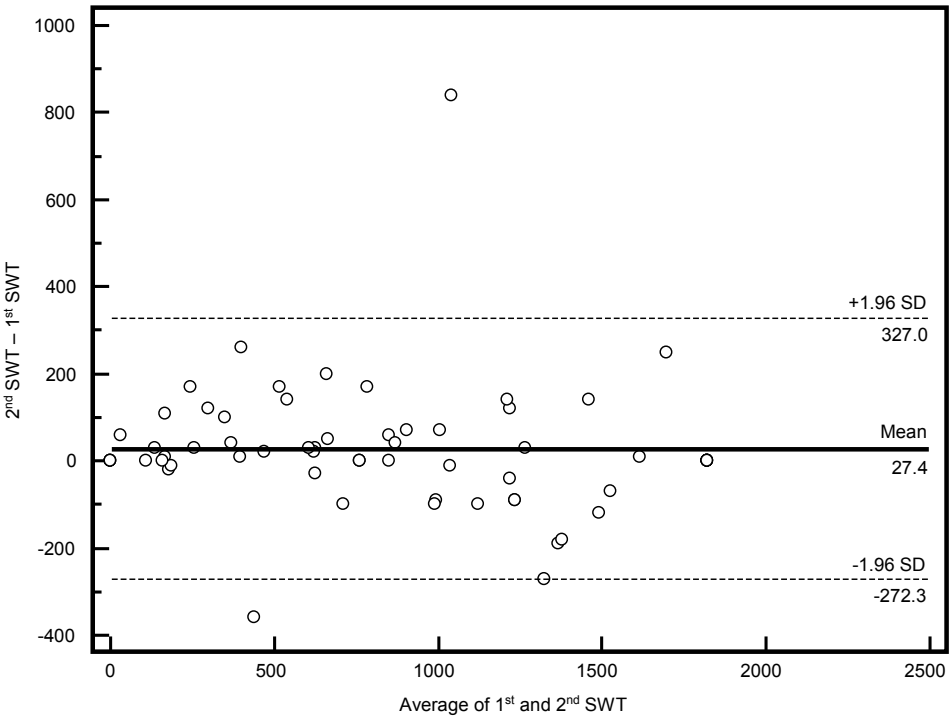

Figure 3.1. Bland and Altman plot of the distance walked (in metres) on 2 SWTs.

Study limitations

When interpreting the results, it should be considered that the SWT might be influenced by the patients' cognitive status, which was not assessed specifically. Just as with other performance tests that require instructions, patients' cognitive status will need to be considered when using the SWT in clinical practice, and clear instructions must be given. Furthermore, it can be helpful to demonstrate more than 1 stage. A limitation of this study is that the SWT was conducted in groups, whereas the 6MWT was performed individually. Six participants performed the SWT individually as well as in a group, showing about the same results. However, a larger sample, comparing individual performance on the SWT with performance in a group, needs further study.

Conclusions

The SWT can be performed in groups and requires less space to conduct than the 6MWT. This, together with its sound measurement properties, favors the use of the SWT to determine functional walking capacity, especially for patients after stroke who have a relatively high walking speed.

Acknowledgments

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Chapter 4

Validity and reproducibility of the Functional Gait Assessment in persons after stroke

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Abstract

Objective. To evaluate construct validity and reproducibility of the Functional Gait Assessment (FGA) for measuring walking balance capacity in persons after stroke.

Design. Cross-sectional study.

Setting. Inpatient and outpatient rehabilitation center.

Subjects. Fifty-two persons post-stroke (median (25% and 75% percentiles)) time post-stroke 6 (5–10) weeks) with independent walking ability (mean gait speed 1.1 ± .4 m/s).

Methods. Subjects completed a standardized FGA twice within one to eight days by the same investigator. Validity was evaluated by testing hypotheses on the association with two timed walking tests, Berg Balance Scale, and the mobility domain of the Stroke Impact Scale using correlation coefficients (*r*), and with Functional Ambulation Categories using the Kruskal-Wallis test. Reproducibility of FGA scores was assessed with intraclass correlation coefficient and standard error of measurement.

Results. Subjects scored a median of 22 out of 30 points at the first FGA. Moderate to high significant correlations (*r* .61–.83) and significant differences in FGA median scores between the Functional Ambulation Categories were found. Eight hypotheses (80%) could be confirmed. Inter-rater, intrarater, and test-retest reliability of the total scores were excellent. The standard error of measurement and minimal detectable change were 2 and 6 points, respectively. No relevant ceiling effect was observed.

Conclusion. The FGA demonstrated good measurement properties in persons after stroke and yielded no ceiling effect in contrast to other capacity measures. In clinical practice, a measurement error of 6 points should be taken into account in interpreting changes in walking balance.

Introduction

Regaining walking balance is an important goal in stroke rehabilitation. Balance impairments in persons after stroke are common and have a large impact on the patient's ability to walk and hence their independence in daily life.[1-3] Furthermore, balance impairments are associated with an increased risk of falls.[3-5] During rehabilitation, walking balance is usually monitored through standardized clinical tests such as the Functional Ambulation Categories and Timed Up and Go Test which includes straight line walking in a standardized, controlled environment. However, these tests may not accurately reflect walking balance required for functional, daily life ambulation which is more variable in speed and direction (e.g. turning, stepping sideways, stepping over objects). Assessment of walking balance should include these more variable and challenging skills.

For persons after stroke, the Functional Gait Assessment (FGA) has been used to assess functional walking activities in a standardized way.[6] The FGA attempts to measure the ability of a patient to maintain balance and safety while altering gait. It was developed as a modified version of the Dynamic Gait Index, addressing the shortcomings of the Dynamic Gait Index with respect to test instructions and decision rules for item scoring.[7,8]

Two studies reported measurement properties of the FGA in persons after stroke.[9,10] Both studies reported excellent reproducibility and found moderate to high associations with other measures of balance and gait. Nevertheless, one study had a small sample size (n=28) and the other study included merely persons in the chronic phase after stroke to determine test-retest reliability and measurement error. Construct validity based on associations with patient-reported performance qualifiers was not reported. Besides, in previous studies investigating the FGA, details on the standardization of test administration were lacking.[7,9-17]

Therefore, this cross-sectional study was carried out in order to determine the measurement properties of the FGA (Dutch translation) in persons after stroke. This study examined the construct validity, reproducibility (inter-rater, intra-rater, and test-retest reliability), and interpretability of the FGA. The FGA was administered and scored according to a standardized protocol in persons who were in various stages after stroke.

Methods

Setting

The study was performed in a rehabilitation center between November 2015 and August 2017. The study protocol was approved by the Medical Ethical Committee of the Academic Medical Center Amsterdam (protocol number NL50002.018.14). All participants provided written informed consent.

Study population

A convenience sample was obtained by recruiting persons in all phases after stroke who received inpatient or outpatient rehabilitation care. The inclusion criteria were (1) clinical diagnosis of stroke; (2) age 18 years or older; (3) walking ability without physical assistance (only use of assistive devices and/or orthotics was allowed); and (4) ability to understand and follow the study instructions.

Procedure

Subjects were invited for two separate test sessions of 45 minutes in which the FGA was administered followed by balance and walking tests commonly used in and validated for stroke survivors.[6,18-20] In subjects who suffered their stroke less than 12 weeks before study inclusion, the second session was carried out on the same day to prevent interference from recovery of stroke.[21] In others, the time interval between the two sessions was maximally eight days. Before assessment, subjects were informed about the study procedures. Demographic and disease characteristics were extracted from the medical records of the subjects.

Measurement instruments

FGA. The FGA consists of 10 tasks assessing walking balance.[7] Each item is scored on a 4-point ordinal scale (range 0–3), with lower scores indicating greater impairments, and with a maximum total score of 30 points. Subjects were verbally instructed about the tasks and these tasks were demonstrated when necessary. The subjects completed the FGA in a corridor with a 6-m walkway marked off with tape on a short-pile carpet floor (Figure 4.1). Different colors of tape were used to differentiate between several walkway widths as defined in the grading instructions of most items and thereby simplify the rating process. In clinical practice, direct observations are used, but in order to standardize circumstances, the FGA was videotaped in this study. The FGA protocol used in this study is described in the supplemental material. First, the FGA was translated to Dutch by two authors (M.V.B. and A.B.). Then, test instructions and scoring criteria were specified to allow for uniform administration and scoring (e.g. definitions were provided). For items 7 and 10, stroke-specific instructions were given because of the unilateral impairments (i.e. folding both arms across the chest and forwards stair walking downstairs only when possible with the affected upper extremity).

Berg Balance Scale. The Berg Balance Scale assesses balance of the subject both sitting and standing and was administered during the first test session. It consists of 14 performance tasks, each scored on a 5-point ordinal scale.[18-20] Subjects were verbally instructed about the tasks and these tasks were demonstrated when necessary. The use of walking aids is allowed during the Berg Balance Scale, but assistive devices cannot be used.

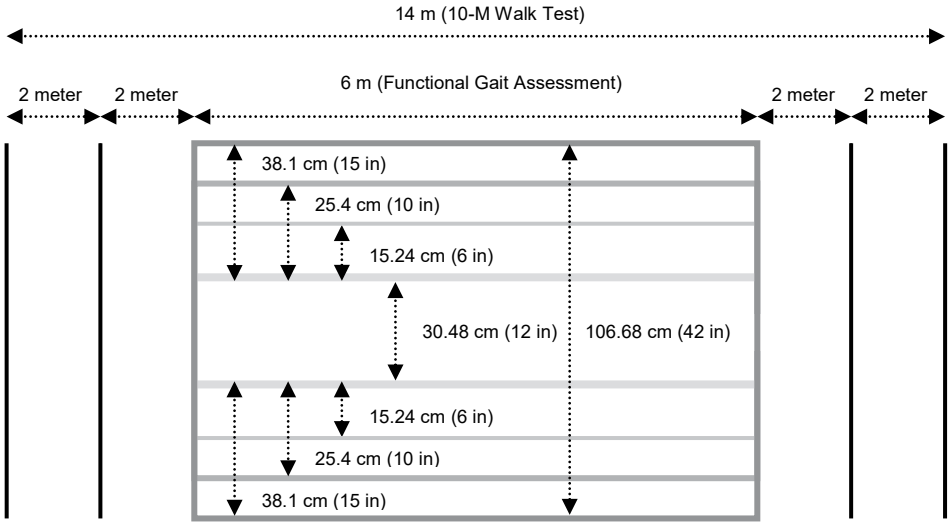

Figure 4.1. Schematic representation of the taped walkway for the Functional Gait Assessment (FGA) and 10-M Walk Test. The distances between the longitudinal lines were measured from the interior side of the taped line to the interior side of the next taped line.

10-M Walk Test. The 10-M Walk Test is a time-scored walking test that measures comfortable gait speed and fast gait speed (no running) along the middle 10 m of a 14-m walkway (Figure 4.1).[6] This measurement instrument was administered during the first test session and the average gait speed of three walking trials was used for analysis.

Functional Ambulation Categories. The Functional Ambulation Categories, administered during the second test session, is a 6-point ordinal scale walking test categorizing walking capacity from 0 (unable to walk) to 5 (independent walking capacity on uneven surface and stairs).[6]

6-Minute Walk Test. The 6-Minute Walk Test, administered during the second test session, was conducted following the protocol of the American Thoracic Society. The test requires subjects to walk over a 40-m long, flat, straight path.[6,22] At either end of the path two cones were placed half a meter apart to avoid abrupt changes of direction. Subjects were instructed to walk back and forth around the cones and cover the largest possible distance in 6 minutes without running.

Mobility domain of the Stroke Impact Scale. The Stroke Impact Scale assesses patient-reported health status following stroke.[23,24] The mobility domain of the Stroke Impact Scale was administered during the second test session. The mobility domain of the Stroke Impact Scale consists of nine items on which the subject scores the difficulty experienced in completing each item. This is done on a 5-point ordinal scale (range 1–5)

with lower scores indicating greater difficulty. The sum score is normalized to a value between 0 and 100.

Data handling and analysis

The investigator (W.B.) who assessed the subjects with the measurement instruments scored the first FGA of each subject from video on two occasions minimally three weeks apart to examine intra-rater reliability. To evaluate test-retest reliability of the FGA, the same investigator scored the two FGAs of each subject with a period of at least one week in between. To determine inter-rater reliability, three physical therapists with 4–37 years of working experience in stroke rehabilitation served as observers. All observers were provided with the FGA and written instructions for administering the test and were trained by the investigator for 2 hours with a practice testing session using one videotaped assessment before video rating the FGA independently.

Construct validity of the FGA was assessed by testing hypotheses. Based on visually inspected normality, the Pearson product-moment correlation coefficient and Spearman rank correlation coefficient were used. The following classification was used: poor (<.25), fair (.25–.49), moderate (.50–.74), good (.75–.89), and excellent (≥.90).[25] The Kruskal-Wallis one-way analysis of variance by ranks was used to determine differences between the FGA total score for the different Functional Ambulation Categories. Moderate to good positive associations between the FGA (first assessment) and the capacity measures (Berg Balance Scale, 10-M Walk Test, and 6-Minute Walk Test) and the patient-reported performance measure (Stroke Impact Scale) were hypothesized. Considering we expected that the FGA better reflects the balance and walking capacity in daily life than the other capacity measures, we hypothesized that the association between the FGA and the patient-reported performance measure (Stroke Impact Scale) is stronger than the association between the capacity measures (Berg Balance Scale, 10-M Walk Test, and 6-Minute Walk Test) and the patient-reported performance measure (Stroke Impact Scale). Furthermore, we hypothesized that the FGA would have good discriminative ability for the Functional Ambulation Categories 3 to 5 by showing significantly different FGA mean values. Construct validity was considered to be adequate in the case where over 75% of the hypotheses were confirmed.[6]

Intra-rater reliability of the FGA was examined using an intraclass correlation coefficient model 3,1 ($ICC_{3,1}$) and a 95% confidence interval (CI). Interrater and test-retest reliability of the FGA were examined using ICCs model 2,1 ($ICC_{2,1}$) and CIs. The same classification was used to interpret both the ICC and the correlation coefficients of validity. Ceiling effect of the FGA was examined by calculating the percentage of the maximum (30 points) test score present in the whole range of test scores for both FGAs. A score equal to or higher than 15% indicates a ceiling effect.[6] Measurement error was reflected by the standard error of measurement ($SEM = SD_{pooled} * \sqrt{(1 - ICC)}$), the Bland-Altman repeatability coefficient (repeatability coefficient = $1.96 * SD_{difference}$), and the

Bland-Altman plot. The SEM was satisfactory if it represented ≤10% of the score range.[26] Furthermore, the minimal detectable change was determined (minimal detectable change = 1.96 * SEM * √2).

To ensure statistical power, a sample size of at least 50 subjects was required.[27] Statistical significance was set at $p<.05$. Statistical analysis was performed using SPSS Statistics 23.0 (SPSS Inc., Chicago, IL, USA).

Results

Subjects

Fifty-two persons after stroke met the selection criteria and signed informed consent. Table 4.1 shows all subject characteristics. Four subjects used assistive devices (walker, cane, or quad cane) and three subjects used walking aids (custom-made ankle-foot orthosis or orthopedic shoes). Forty-eight subjects (92%) repeated the FGA within one day (median of 4 hours in-between (25% and 75% percentiles of 3 and 5 hours, respectively)) and four subjects within eight days. The time required for the FGA ranged from 10 to 15 minutes.

Table 4.1. Subject characteristics (n=52)

Characteristics	Value
Sex, male/female, no. (percentage)	32 (62%) / 20 (38%)
Age (mean ± SD)	62 ± 12 years
Stroke diagnosis (ischemic/haemorrhage), no. (percentage)	39 (75%) / 13 (25%)
Side of hemiplegia (left/right), no. (percentage)	25 (48%) / 27 (52%)
Weeks since stroke onset (median and 25 and 75% percentiles)	6 (5;10)
ADL performance (Barthel Index)	20 (18;20) (n=43)
Body mass index (mean ± SD)	26 ± 4

ADL: Activities of Daily Living.

Construct validity

The outcomes of the FGA and the other measurement instruments are shown in Table 4.2. No ceiling effect (1%) was observed. Results of hypotheses testing are presented in Table 4.3. Good correlations were found between the FGA and the Berg Balance Scale, 10-M Walk Test, and 6-Minute Walk Test (the Spearman rank correlation coefficient .75–.83, $p<.001$). A moderate correlation was found between the FGA and the Stroke Impact Scale (the Spearman rank correlation coefficient .61, $p<.001$) as well as between the Berg Balance Scale, 10-M Walk Test, and 6-Minute Walk Test and the Stroke Impact Scale (the Spearman rank correlation coefficient .53–.63, $p\leq.001$). The Kruskal-Wallis test revealed significant differences in FGA scores ($p<.02$) between the three groups based on Functional Ambulation Category (3, 4, and 5). Median (P25; P75) scores were 11 (7.5; 13.5, n=9), 16 (12.5; 20.3, n=10), and 24 (22; 26, n=33) for category 3, 4, and 5, respectively. Eight of the 10 predetermined hypotheses could be confirmed.

Table 4.2. Functional Gait Assessment and related measurement instruments

Measurement instrument (min-max score)	Mean ± SD or median and 25 and 75% percentiles	Percentage of subjects with maximum score
Functional Gait Assessment first assessment (0-30)	22 (15;25)	2%
Functional Gait Assessment second assessment	23 (16;27)	0%
10-M Walk Test comfortable gait speed	1.1 m/s ± .4 m/s	n.a.
10-M Walk Test maximal gait speed	1.5 m/s ± .5 m/s (n=51)	n.a.
Berg Balance Scale (0-56)	54 (48;56)	33%
6-Minute Walk Test	417 ± 152 m (n=51)	n.a.
Stroke Impact Scale mobility domain (0-100)	80 (69;87) (n=34)	0%
Functional Ambulation Categories (0-5)	5 (4;5)	64%

n.a.: not applicable.

Reproducibility and measurement error

Intra-rater reliability, inter-rater reliability between three observers and test-retest reliability were excellent (Table 4.4). On item level of the FGA, intra-rater reliability showed good to excellent ICCs, whereas inter-rater and test–retest reliability showed poor to excellent ICCs (Table 4.4). A significant difference between repeated FGAs was found with higher scores at the retest (mean difference of .9±2.8 points, p=.03). The repeatability coefficient was 5.6 points and the Bland-Altman plot revealed no heteroscedasticity (Figure 4.2). The SEM was 2.1 points (10%) and the minimal detectable change was 5.7 points (28% of the weighted mean).

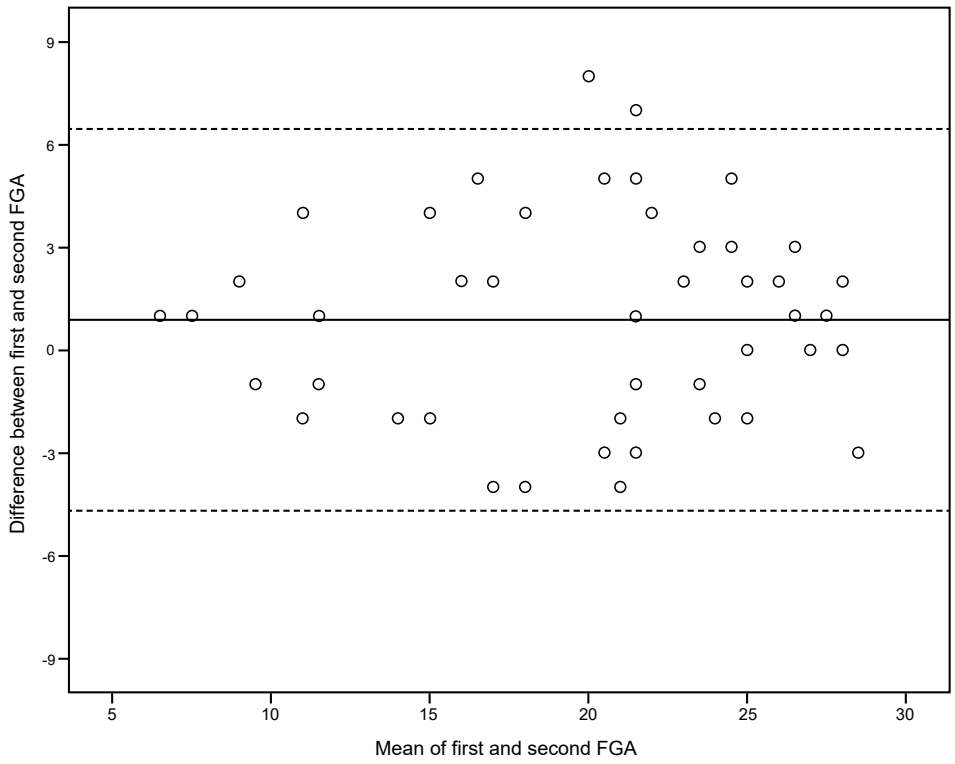

Figure 4.2. Bland-Altman plot of Functional Gait Assessments (FGA).

Table 4.3. Hypotheses for construct validity of Functional Gait assessment, with expected and observed test results

Hypotheses	Association between	Expected	Observed[a]	Hypothesis confirmed
Moderate to good associations are expected between the FGA and the capacity measures (10MWT, BBS, and 6MWT).	FGA and 10MWT comf.	r = .50-.89	r = .80	Yes
	FGA and 10MWT max.	r = .50-.89	r = .75	Yes
	FGA and BBS	r = .50-.89	r = .83	Yes
	FGA and 6MWT	r = .50-.89	r = .78	Yes
A moderate to good association was expected between the FGA and the patient-reported performance measure (SIS).	FGA and SIS	r = .50-.89	r = .61	Yes
The association between FGA and the patient-reported performance measure (SIS) is expected to be stronger than the association between the capacity measures (BBS, 10MWT, and 6MWT) and SIS (<r FGA-SIS).	SIS and 10MWT comf.	<r FGA-SIS	r = .62	No
	SIS and 10MWT max.	<r FGA-SIS	r = .63	No
	SIS and BBS	<r FGA-SIS	r = .56	Yes
	SIS and 6MWT	<r FGA-SIS	r = .53	Yes
	Difference between			
The FGA discriminates between FAC 3, 4, and 5 by showing statistically significant differences in FGA-scores between the FAC.	FAC 3 and FAC 4	p<.05	p<.001	Yes
	FAC 4 and FAC 5		p=.018	

FGA: Functional Gait Assessment; 10MWT comf.: 10-M Walk Test comfortable gait speed; 10MWT max.: 10-M Walk Test maximal gait speed; BBS: Berg Balance Scale; 6MWT: 6-Minute Walk Test; SIS: Stroke Impact Scale; r: Spearman rank correlation coefficient; FAC: Functional Ambulation Categories.

[a] Spearman correlation coefficient (p≤.001) was used for all hypotheses except the last for which the Kruskal-Wallis test was used.

Table 4.4. Inter-rater, intra-rater, and test-retest reproducibility of the Functional Gait Assessment (item and total scores)

Item	Inter-rater $ICC_{2.1}$ (CI)	Intra-rater $ICC_{3.1}$ (CI)	Test-retest $ICC_{2.1}$ (CI)
1 Gait level surface	.85 (.78–.91)	.99 (.98–.99)	.62 (.42–.76)
2 Change in gait speed	.53 (.37–.67)	.86 (.76–.92)	.80 (.68–.88)
3 Gait with horizontal head turns	.67 (.54–.78)	.92 (.87–.95)	.46 (.22–.65)
4 Gait with vertical head turns	.58 (.43–.72)	.87 (.78–.92)	.40 (.15–.61)
5 Gait and pivot turn	.74 (.63–.83)	.98 (.97–.99)	.61 (.41–.76)
6 Step over obstacle	.91 (.86–.95)	.98 (.97–.99)	.88 (.80–.93)
7 Gait with narrow base of support	.78 (.65–.87)	.96 (.94–.98)	.84 (.74–.91)
8 Gait with eyes closed	.96 (.94–.98)	.97 (.94–.98)	.16 (-.11–.41)
9 Ambulating backwards	.61 (.46–.73)	.84 (.74–.91)	.74 (.59–.84)
10 Steps	.92 (.88–.95)	1.00 (1.00–1.00)	.95 (.92–.97)
Total	.93 (.89–.96)	.99 (.97–.99)	.90 (.82–.94)

ICC (CI): Intraclass correlation coefficient model 2,1 or 3,1 (95% confidence interval).

Discussion

The present study confirmed the validity of the FGA and demonstrated excellent reproducibility in persons after stroke. It was shown that a score difference of at least 6 points can be interpreted as a real change of walking balance capacity in individuals. No relevant ceiling effect was observed.

The results confirm findings of earlier validation studies investigating the association between the FGA and balance and gait capacity qualifiers in persons after stroke.[9,10] Our hypotheses on associations of the FGA with related measurement instruments were confirmed. No relevant ceiling effect was observed for the FGA, in contrast to the large ceiling effect for the Berg Balance Scale and the Functional Ambulation Categories (one-third and more than half the group, respectively). Hence, the FGA is probably more sensitive than the Functional Ambulation Categories to evaluate walking balance in independently ambulating persons after stroke.

The strength of the association between the FGA and perceived limitations in mobility, assessed with the Stroke Impact Scale, was lower than expected. We expected that the FGA better reflects the balance and walking performance in daily life. The moderate association between the FGA and Stroke Impact Scale may be due to the fact that the mobility domain of the Stroke Impact Scale includes more than merely self-reported walking activities, whereas the FGA only focuses on walking capacity. Furthermore, the majority of the subjects were in the early phase after stroke. Therefore, judging their experiences on several items of the Stroke Impact Scale could be more difficult or impossible. Finally, the correlation coefficient between the FGA and Stroke Impact Scale is based on a smaller sample due to missing data, which compromises the reliability of the coefficient.

As recommended in earlier studies on the reproducibility of the FGA, we standardized the administration of the FGA by adapting the test instructions and scoring criteria (supplemental material).[7,10,12] This protocol is feasible and it takes about 10–15 minutes to administer the FGA depending on the vitality of the person. In this study, a corridor of the rehabilitation center was used to perform the walking tests. The FGA measures clinically

and functionally relevant walking tasks. Early insight in a person's functional status is important for goal setting and patient management. Persons in the early phase after stroke receiving inpatient rehabilitation have not yet experienced most of these challenges in daily life ambulation. Therefore, besides evaluation of these walking tasks, it includes a new experience and practice session. Moreover, this approach to task training is consistent with principles of motor learning, where meaningful tasks and challenging learning can facilitate neuroplasticity.[28] Clinicians can use task elements and adapt the challenging tasks for further practice of walking balance capacity during the therapy sessions. The subjects who participated in this study experienced the FGA as a challenging and useful assessment.

Results on reproducibility of the total scores were excellent and comparable with other studies in persons after stroke, healthy adults, and persons with vestibular disorders.[7,9,10,16] Therefore, the FGA is appropriate for research purposes. Nevertheless, agreement between the observers on item level varied and for some items, agreement was poor. Items 2 ("change in gait speed"), 3 ("gait with horizontal head turns"), 4 ("gait with vertical head turns"), and 9 ("ambulating backwards") showed the lowest agreement (Table 4.4). The item scoring in the FGA is based on a subjective judgment of the extent of gait speed variation, rotation of the head, gait speed backwards, and stability. It is therefore strongly recommended to obtain agreement between observers on the test procedure and to administer the FGA in a research or clinical setting to improve inter-rater reliability on item level.[7]

A minimal detectable change of 6 points was found in this study, which is within the range of measurement error commonly found in measurement instruments with ordinal scales. Test-retest reliability of item scores was quite variable and for some items it was poor. Test-retest reliability was especially low for the items 1 ("gait level surface"), 3 ("gait with horizontal head turns"), 4 ("gait with vertical head turns"), 5 ("gait and pivot turn"), and 8 ("gait with eyes closed"). This may be due to variability in balance control and learning effect. Most subjects performed the retest session on the same day. Marchetti et al.[13] calculated a minimal detectable change of 6 points in a large population of persons with balance and vestibular disorders, which is in line with the present study. Lin et al.[9] found a smaller minimal detectable change. In their study, persons in the chronic phase after stroke (more than one year after stroke) were included. In our study, most subjects were in the first 12 weeks after stroke. Hence, their walking balance may have been more variable. Nevertheless, monitoring of walking balance is especially important in the early phase after stroke.

Some study limitations need to be addressed. We investigated the FGA through video observations and this may differ from assessments in clinical practice based on direct observations, although it has been shown that differences in inter-rater reliability found between video and direct observations are negligible.[10] A second limitation is that we included persons who were able to walk without assistance (Functional Ambulation

Categories levels 3–5). In this population, the FGA is most useful. Only four subjects used an assistive device during the assessments. The results of this study are only generalizable to a similar population.

Further studies are recommended on several aspects of the FGA in persons after stroke. This study showed a moderate association between the FGA and the patient-reported performance measure (Stroke Impact Scale). Because data on the mobility domain of the Stroke Impact Scale was only available from 34 subjects, this association needs to be confirmed. Moreover, there are two suggestions for improvement of the FGA protocol. The first suggestion is to inspect the maximal horizontal and vertical head turn while the individual is standing still before assessing this task during walking (items 3 and 4). In this way, the observer gets insight in the maximal active range of motion when turning the head and whether the person understands the task. Second, item 9 ("ambulating backwards") may be improved by quantifying good, slower, and slow gait speed as done for items 1 and 8. With these modifications, inter-rater reliability should be re-assessed. Further studies should explore whether the application of Item Response Theory models can improve test administering and scoring, as was recently done for the FGA in persons with Parkinson's disease.[12] Future research should also gain insight in the predictive validity of the FGA in classifying fall risk in this population. Finally, the minimal clinically important difference in FGA outcome should be determined.

In conclusion, our findings indicate that the FGA, administered and scored according to a standardized protocol, is a feasible, valid, and reliable instrument to assess walking balance in persons after stroke with independent ambulation capacity. Taking less than 15 minutes to administer, the instrument has clinical utility for use in persons after stroke to evaluate walking balance and to guide walking balance training. An advantage of the FGA is the absence of a ceiling effect, in contrast to the ceiling effect observed for the Functional Ambulation Categories in a study population with relatively minor walking deficits. For monitoring walking balance in individuals with stroke, changes of at least 6 points can be interpreted as real changes.

Clinical messages

- The Functional Gait Assessment is a valid and reliable tool to objectively quantify walking balance in persons after stroke.
- The Functional Gait Assessment provides detailed insight in functional gait deficits and can identify targets for training of walking balance.
- For individual monitoring, a change in the Functional Gait Assessment score of at least 6 points can be considered a real change in walking balance.

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Supplement 4.1.

Protocol and administration form of the Functional Gait Assessment (FGA).

This protocol is based on the instructions described by Wrisley et al. (Phys Ther. 2004). In the formulation of the instructions for subjects, the stroke-specific disabilities are taken into account (i.e., paresis of the upper extremity and reduced cognitive ability to understand test instructions). A footnote is added when a test instruction is only applicable to subjects with unilateral impairments.

Purpose of the FGA

To evaluate walking balance performance.

Requirements

- Marked 6-m (20-ft) walkway (Figure 1);
- Two cones;
- Administration form (included in this protocol);
- Stopwatch;
- Two boxes of any material or shoe boxes (l x d x h = 39.37 x 17.78 x 11.43 cm = 15.5 x 7.0 x 4.5 in);
- Stairs with rails;
- Any assistive devices and/or orthotics when required for the subject to walk;
- Chair present for resting; and
- Blindfold (optional).

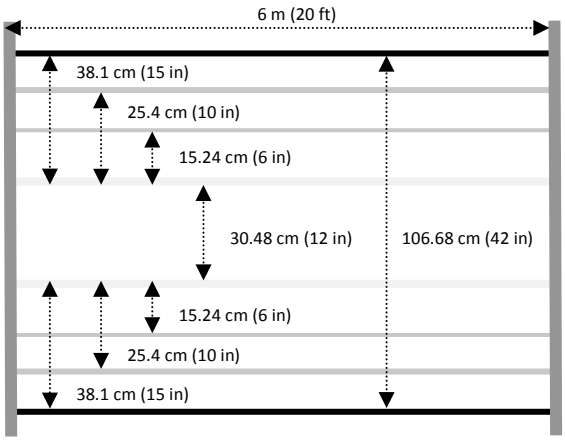

Figure 1. Schematic representation of a marked walkway with cones for the Functional Gait Assessment. The thick vertical lines are the starting and stopping lines. We used different colours for the lines and measured the distances from the interior side of a line to the interior side of the next line to make administration easier. (Optional: Every 1.5 m [5 ft] for item 2 and 3.6 m [12 ft] for item 7 can also be marked on the wall or floor.)

Instructions for the assessor

The subject stands between the first cone and the starting line and starts walking from the starting line to beyond the stopping line (6 meters). Cones are standing 2 meters outside the walkway. The assessor starts the stopwatch when the subject crosses the starting line and stops the time when the subject crosses the stopping line. When needed to ensure safety, the assessor accompanies the subject by walking slightly behind and to the affected side of the subject (supervision). The tasks are verbally instructed and demonstrated when necessary. During the test further encouragement is avoided. A task may be repeated but only when the instructions were misunderstood, or there is another reason why the test performance is below expectation. Use of an orthosis is allowed on all items (but is scored as a mild gait deviation). Deviations from the walkway width are defined as standing on or passing the longitudinal line. Assistance is defined as physical assistance or reaching for a wall. All 10 items have a minimum score of 0 and a maximum of 3 points.

Items (extensive description)

Instruction beforehand: *"Walk to the cone at all items. Start after the command '3, 2, 1, start'."*

1. GAIT LEVEL SURFACE

Specific requirements: Stopwatch.

Instructions: *"Walk at your comfortable speed from here to the cone. Time is measured."*

Grading: Mark the highest category that applies.

3 *Normal* – Walks 6 m (20 ft) in less than 5.5 seconds, no assistive devices, no evidence for imbalance, normal gait pattern, deviates no more than 15.24 cm (6 in) outside of the 30.48-cm (12-in) walkway width.

2 *Mild impairment* – Walks 6 m (20 ft) in 5.5–7 seconds, uses an assistive device, mild gait deviations, or deviates 15.24–25.4 cm (6–10 in) outside of the 30.48-cm (12-in) walkway width.

1 *Moderate impairment* – Walks 6 m (20 ft) in more than 7 seconds, abnormal gait pattern, evidence for imbalance, or deviates 25.4–38.1 cm (10–15 in) outside of the 30.48-cm (12-in) walkway width.

0 *Severe impairment* – Cannot walk 6 m (20 ft) without assistance, severe gait deviations or imbalance, deviates greater than 38.1 cm (15 in) outside of the 30.48-cm (12-in) walkway width or reaches and touches the wall.

2. CHANGE IN GAIT SPEED

Instructions: *"Begin walking at your comfortable pace."* (for 1.5 m [5 ft]). *"When I tell you 'quick', walk as fast as you can."* (for 1.5 m [5 ft]). *"When I tell you 'slow', walk as slowly as you can." (for 1.5 m [5 ft]).*

Grading: Mark the highest category that applies.

3 *Normal* – Able to smoothly change walking speed without loss of balance or gait deviation. Shows a significant difference in walking speeds between comfortable, fast, and slow speeds. Deviates no more than 15.24 cm (6 in) outside of the 30.48-cm (12-in) walkway width.

2 *Mild impairment* – Is able to change speed but demonstrates mild gait deviations, deviates 15.24–25.4 cm (6–10 in) outside of the 30.48-cm (12-in) walkway width, or no gait deviations but unable to achieve a significant change in velocity, or uses an assistive device.

1 *Moderate impairment* – Makes only minor adjustments to walking speed, or accomplishes a change in speed with significant gait deviations, deviates 25.4–38.1 cm (10–15 in) outside the 30.48-cm (12-in) walkway width, or changes speed but loses balance but is able to recover and continue walking.

0 *Severe impairment* – Cannot change speeds, deviates greater than 38.1 cm (15 in) outside 30.48-cm (12-in) walkway width, or loses balance and has to reach for wall or be caught.

3. GAIT WITH HORIZONTAL HEAD TURNS

Instructions: *"Walk from here to the cone. Begin walking at your comfortable pace. Keep walking straight; after 3 steps, turn your head to the right and keep walking straight while looking to the right. After 3 more steps, turn your head to the left and keep walking straight while looking left. Continue alternating looking right and left every 3 steps until you have completed 2 repetitions in each direction. I will indicate when to turn the head 'right' and 'left'. Turn your head maximally."*

Grading: Mark the highest category that applies.

3 *Normal* – Performs head turns smoothly with no change in gait. Deviates no more than 15.24 cm (6 in) outside 30.48-cm (12-in) walkway width.

2 *Mild impairment* – Performs head turns smoothly with slight change in gait velocity (e.g., minor disruption to smooth gait path), deviates 15.24–25.4 cm (6–10 in) outside 30.48-cm (12-in) walkway width, or uses an assistive device.

1 *Moderate impairment* – Performs head turns with moderate change in gait velocity, deviates 25.4–38.1 cm (10 –15 in) outside 30.48-cm (12-in) walkway width but recovers, can continue to walk.

0 *Severe impairment* – Performs task with severe disruption of gait (e.g., staggers 38.1 cm [15 in] outside 30.48-cm [12-in] walkway width, loses balance, stops, or reaches for wall).

4. GAIT WITH VERTICAL HEAD TURNS

Instructions: *"Walk from here to the cone. Begin walking at your comfortable pace. Keep walking straight; after 3 steps, tip your head up and keep walking straight while looking up. After 3 more steps, tip your head down, keep walking straight while looking down. Continue alternating looking up and down every 3 steps until you have completed 2 repetitions in each direction. I will indicate when to look 'up' and 'down'. Tip your head maximally."*

Grading: Mark the highest category that applies.

3 *Normal* – Performs head turns with no change in gait. Deviates no more than 15.24 cm (6 in) outside 30.48-cm (12-in) walkway width.

2 *Mild impairment* – Performs task with slight change in gait velocity (e.g., minor disruption to smooth gait path), deviates 15.24–25.4 cm (6–10 in) outside 30.48-cm (12-in) walkway width or uses an assistive device.

1 *Moderate impairment* – Performs task with moderate change in gait velocity, slows down, deviates 25.4–38.1 cm (10–15 in) outside 30.48-cm (12-in) walkway width but recovers, can continue to walk.

0 *Severe impairment* – Performs task with severe disruption of gait (e.g., staggers, 38.1 cm [15 in] outside 30.48-cm [12-in] walkway width, loses balance, stops, reaches for wall).

5. GAIT AND PIVOT TURN

Specific requirements: Stopwatch.

Instructions: *"Begin with walking at your comfortable pace. When I tell you, 'turn and stop', turn as quickly as you can to face the opposite direction and stop. Time of turning is measured."*

Grading: Mark the highest category that applies.

3 *Normal* – Pivot turns safely within 3 seconds and stops quickly with no loss of balance. No use of an assistive device.

2 *Mild impairment* – Pivot turns safely in >3 seconds and stops with no loss of balance, or pivot turns safely within 3 seconds and stops with mild imbalance, requires small steps to catch balance.

1 *Moderate impairment* – Turns slowly (>3 seconds), requires verbal cueing, or requires several small steps to catch balance following turn and stop.

0 *Severe impairment* – Cannot turn safely, requires assistance to turn and stop.

6. STEP OVER OBSTACLE

Specific requirements: Two boxes (39.37 x 17.78 x 11.43 cm [5.5 x 7.0 x 4.5 in] each).
Instructions: *"Begin walking at your comfortable speed. When you come to the box, step over it, not around it, and keep walking."*
Grading: Mark the highest category that applies.

3 *Normal* – Is able to step over 2 boxes together (22.86 cm [9 in] total height) without changing gait speed. No evidence of imbalance and no use of an assistive device.
2 *Mild impairment* – Is able to step over one box (11.43 cm [4.5 in] total height) without changing gait speed; no evidence of imbalance.
1 *Moderate impairment* – Is able to step over one box (11.43 cm [4.5 in] total height) but must slow down and adjust steps to clear box safely. May require verbal cueing.
0 *Severe impairment* – Cannot perform without assistance.

7. GAIT WITH NARROW BASE OF SUPPORT

Instructions: *"Walk on the floor with one*[I] *or two arms folded across the chest, feet aligned heel to toe in tandem."* (for a distance of 3.6 m [12 ft]). *"The number of steps taken in a straight line are counted for a maximum of 10 steps."*
Grading: Mark the highest category that applies.

3 *Normal* – Is able to ambulate for 10 steps heel to toe with no staggering.
2 *Mild impairment* – Ambulates 7–9 steps.
1 *Moderate impairment* – Ambulates 4–6 steps.
0 *Severe impairment* – Ambulates less than 4 steps heel to toe or cannot perform without assistance or uses an assistive device.

8. GAIT WITH EYES CLOSED

Specific requirements: Stopwatch and blindfold (optional).
Instructions: *"Walk at your comfortable speed from here to the cone with your eyes closed/with blindfold. I will tell you when to stop. Time is measured."*

[I] One arm folded is only applicable to subjects with unilateral impairments.

Grading: Mark the highest category that applies.

3 *Normal* – Walks 6 m (20 ft) in less than 7 seconds, no assistive devices, no evidence of imbalance, normal gait pattern, deviates no more than 15.24 cm (6 in) outside 30.48-cm (12-in) walkway width.

2 *Mild impairment* – Walks 6 m (20 ft) in 7–9 seconds, uses an assistive device, mild gait deviations, deviates 15.24–25.4 cm (6–10 in) outside 30.48-cm (12-in) walkway width.

1 *Moderate impairment* – Walks 6 m (20 ft) in more than 9 seconds, abnormal gait pattern, evidence for imbalance, deviates 25.4–38.1 cm (10–15 in) outside 30.48-cm (12-in) walkway width.

0 *Severe impairment* – Cannot walk 6 m (20 ft) without assistance, severe gait deviations or imbalance, deviates greater than 38.1 cm (15 in) outside 30.48-cm (12-in) walkway width or will not attempt task.

9. AMBULATING BACKWARDS

Instructions: *"Walk backwards on a comfortable walking speed until I tell you to stop."*

Grading: Mark the highest category that applies.

3 *Normal* – Walks 6 m (20 ft), no assistive devices, good speed, no evidence for imbalance, normal gait pattern, deviates no more than 15.24 cm (6 in) outside 30.48-cm (12-in) walkway width.

2 *Mild impairment* – Walks 6 m (20 ft), uses an assistive device, slower speed, mild gait deviations, deviates 15.24–25.4 cm (6–10 in) outside 30.48-cm (12-in) walkway width.

1 *Moderate impairment* – Walks 6 m (20 ft), slow speed, abnormal gait pattern, evidence for imbalance, deviates 25.4–38.1 cm (10–15 in) outside 30.48-cm (12-in) walkway width.

0 *Severe impairment* – Cannot walk 6 m (20 ft) without assistance, severe gait deviations or imbalance, deviates greater than 38.1 cm (15 in) outside 30.48-cm (12-in) walkway width or will not attempt task.

10. STEPS

Instructions: *"Walk up these stairs as you would at home. Use the rail if necessary. At the top turn around and walk down. Walk backwards down only if necessary*[II]*."*

Grading: Mark the highest category that applies.

3 *Normal* – Alternating feet, no rail.

2 *Mild impairment* – Alternating feet, must use rail.

1 *Moderate impairment* – Two feet to a stair or is walking backwards.

0 *Severe impairment* – Cannot do safely.

[II] Walking backwards down is only applicable to subjects with unilateral impairments.

Administration form Functional Gait Assessment

Item 1. Gait level surface (6 meter)				
	Gait speed	**Imbalance**	**Gait deviations**	**Gait width**
3 (normal)	<5.5 sec.	n.a.	n.a.	Until grey line
2 (mild impairment)	5.5–7 sec.	Assistive device	Mild	Until dark grey line
1 (moderate impairment)	>7 sec.	Evident	Evident	Until black line
0 (severe impairment)		Severe	Severe	Crosses black line

Item 2. Change in gait speed for every 1.5 meter				
	Adjustments in gait speed	**Imbalance**	**Gait deviations**	**Gait width**
3 (normal)	Significant	n.a.	n.a.	Until grey line
2 (mild impairment)	Moderate	Assistive device	Mild	Until dark grey line
1 (moderate impairment)	Minor	Evident	Evident	Until black line
0 (severe impairment)	None	Severe	Severe	Crosses black line

Item 3. Gait with horizontal head turns every 3 steps (2 alternating repetitions right and left)			
	Deviations in gait speed	**Imbalance**	**Gait width**
3 (normal)	n.a.	n.a.	Until grey line
2 (mild impairment)	Mild	Assistive device	Until dark grey line
1 (moderate impairment)	Evident	Evident	Until black line
0 (severe impairment)	Stops during head turn	Severe	Crosses black line

Item 4. Gait with vertical head turns every 3 steps (2 alternating repetitions up and down)			
	Deviations in gait speed	**Imbalance**	**Gait width**
3 (normal)	n.a.	n.a.	Until grey line
2 (mild impairment)	Mild	Assistive device	Until dark grey line
1 (moderate impairment)	Evident	Evident	Until black line
0 (severe impairment)	Stops during head turn	Severe	Crosses black line

Item 5. Gait and 180˚ pivot turn			
	Turning speed and imbalance during stopping		**Assistance**
3 (normal)	Pivot turns safely in ≤3 sec. and stops quickly with no loss of balance		n.a.
2 (mild impairment)	Pivot turns safely in >3 sec. with no loss of balance	Pivot turns safely in ≤3 sec. turning but requires small steps to catch balance	Assistive device
1 (moderate impairment)	Pivot turns in >3 sec. and requires several small steps to catch balance following turn and stop		Verbal cues
0 (severe impairment)	Requires assistance to turn and stop		

Item 6. Step over obstacle		
	Number of boxes and gait and balance deviations	**Assistance**
3 (normal)	2 boxes without deviations	n.a.
2 (mild impairment)	1 box without deviations	Assistive device
1 (moderate impairment)	1 box but must slow down and/or adjust step to clear box safely	Verbal cues
0 (severe impairment)	Cannot perform without assistance	

Item 7. Gait with narrow base of support for 3.6 meter	
	Number of steps with feet aligned heel to toe in tandem
3 (normal)	10 steps
2 (mild impairment)	7–9 steps
1 (moderate impairment)	4–6 steps
0 (severe impairment)	≤3 steps or cannot perform without assistive device or assistance

Item 8. Gait with eyes closed (6 meter)				
	Gait speed	**Imbalance**	**Gait deviations**	**Gait width**
3 (normal)	<7 sec.	n.a.	n.a.	Until grey line
2 (mild impairment)	7–9 sec.	Assistive device	Mild	Until dark grey line
1 (moderate impairment)	>9 sec.	Evident	Evident	Until black line
0 (severe impairment)		Severe	Severe	Crosses black line

Item 9. Ambulating backwards (6 meter)				
	Gait speed	**Imbalance**	**Gait deviations**	**Gait width**
3 (normal)	Good	n.a.	n.a.	Until grey line
2 (mild impairment)	Slower	Assistive device	Mild	Until dark grey line
1 (moderate impairment)	Slow	Evident	Evident	Until black line
0 (severe impairment)		Severe	Severe	Crosses black line

Item 10. Steps		
	Mode of stair walking	**Stair walking downstairs[III]**
3 (normal)	Alternating feet, no rail	Forwards
2 (mild impairment)	Alternating feet, must use rail	
1 (moderate impairment)	Two feet to a stair, must use rail	Backwards
0 (severe impairment)	Cannot perform safely	
[III] Walking backwards down is only applicable to subjects with unilateral impairments.		

Administration form

In this form we described the colours of the tape instead of the distances to make administering the FGA easier. Therefore, we used the colours of Figure 1: grey (15.24 cm; 6 in), dark grey (25.4 cm; 10 in), and black (38.1 cm; 15 in). Score only a 3 when all the criteria are fully met. A lower score is obtained if one of the criteria is in a lower order. The administration form can be used as a decision tree. The assessor can mark the grade or mark aspects of the categories to come to the grade of an item. A blank space means that there is no criterion on the basis of that grade (the latter criterion also applies in that column for that row). 'N.a.' means that the deficit is not present or assistance is not needed (not applicable).

Definitions

The following definitions apply to a large number of items.

Evident imbalance: Subject loses balance but is able to recover (without assistance) and continues walking.

Severe imbalance: Subject loses balance and can only regain control by using assistance.

Mild gait deviation: The subject uses an orthotic device or small gait pattern deviations are observable which limit walking minimally (described according to Perry et al. [Slack Inc. 1992]). For example mid foot contact at initial contact, hyperextension of the knee during midstance, etc.

Evident gait deviation: Clear gait deviations whereby the subject is obviously hindered during walking (described according to Perry et al. [Slack Inc. 1992]). For example insufficient foot clearance, circumduction to obtain foot clearance, insufficient stability to stand well on the affected leg, clearly asymmetrical gait pattern, etc.

Severe gait deviation: Subject cannot perform the task due to severely limited gait (and/or imbalance).

Moderate adjustment in gait speed (item 2): There is a noticeable difference between the gait speeds 'comfortable' and the adjusted speeds 'slow' and 'fast' but this difference is smaller than normally expected.

Minor adjustment in gait speed (item 2): The difference between the gait speeds 'comfortable', 'fast' and 'slow' is minimal.

Mild deviation in gait speed (items 3 and 4): Performs head turns smoothly with slight change in gait velocity (e.g., minor disruption to smooth gait path).

Evident deviation in gait speed (items 3 and 4): Markedly reduced gait speed during head turn compared to the comfortable gait speed (gait speed item 1) without completely standing still.

Chapter 5

Concurrent validity and reliability of a low-cost gait analysis system for assessment of spatiotemporal gait parameters

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Abstract

Objective. To determine the concurrent validity and reliability of a low-cost spatiotemporal gait analysis system for clinical use in rehabilitation medicine.
Design. Cross-sectional study.
Subjects. Thirty-three healthy adults.
Methods. The spatiotemporal gait analysis system consists of a video camera placed perpendicular to a 10-m walkway and calibrated for spatial reference. The conditions evaluated in this study were: barefoot walking at comfortable and slow speed, toe and shod walking using a stationary camera setup and barefoot walking at comfortable speed using a moving camera setup. The GAITRite® was used as reference.
Results. High intraclass correlation coefficients (ICC≥0.97; 95% lower limit confidence intervals (95% CIs) ≥0.77) were found between systems for step and stride length, and step, stance and stride time, across setups and conditions. Standard error of measurement and Bland-Altman repeatability coefficients were ≤2.4% and ≤6.3%, respectively. A minimum of 4 footsteps was required to obtain ICC >0.90 and coefficient of variation <10%. For double support and swing time, ICCs were generally low (ICC≥0.21). Inter-rater reliability was excellent for step length, step and stance time (ICC≥0.94; lower limit 95% CIs ≥0.86).
Conclusion. The spatiotemporal gait analysis system is valid and reliable for assessing spatiotemporal parameters in different walking conditions. However, the validity of double support and swing time could not be confirmed.

Lay abstract

Gait parameters, such as step length and step time, allow the quantification of gait deviations in persons with various diseases. Treatment can be customized and evaluated based on these parameters. However, few low-cost, easily applicable systems are available for clinical settings to accurately measure gait parameters. A low-cost spatiotemporal gait analysis system was developed and this study evaluated its accuracy and reliability. The spatiotemporal gait analysis system consists of a camera placed perpendicular to the walkway, which can be used stationary or moved manually along a parallel rail system to capture multiple strides of an individual during a single walk. Thirty-three healthy adults completed trials of barefoot, toe and shod walking. These adults were simultaneously recorded using an electronic walkway, the GAITRite®, for comparison. The results showed that the spatiotemporal gait analysis system is an accurate and reliable system to assess step and stride length, step, stance, and stride time, but not to assess double support and swing time.

Introduction

Gait deviations are among the most commonly reported impairments in persons with a variety of neurological and musculoskeletal conditions.[1-7] Evaluation of the effectiveness of interventions targeting gait requires sensitive and objective assessment of gait characteristics.[8] Gait speed is the outcome most often used in clinical practice, and commonly assessed with timed walking tests, such as the 10-m and 6-min walk test, using a designated track and stopwatch. However, these methods are limited for assessing other spatial and temporal parameters that are considered important to properly evaluate gait, such as step length and step time and derivative parameters such as gait symmetry.[8-11] The validity of simple measurement methods, such as the stopwatch-footfall count method to assess step length, has not been confirmed.[12] Clinical evaluation of these spatiotemporal characteristics is essential for identifying and understanding gait deviations, guiding clinical decision-making, customizing treatment, monitoring individual progress, and proving treatment benefits.[1-6]

Valid and reliable systems assessing spatiotemporal gait parameters include 3-dimensional motion capture systems, and electronic walkways, such as the GAITRite® system.[13-18] However, these systems are relatively costly and, regarding the 3-dimensional systems, too sophisticated for measuring spatiotemporal variables in a clinical setting. In case of electronic walkways, there may be practical issues, such as with restricting the subjects to walk within the relatively narrow width of the carpet and requiring them to walk on and off the carpet.[19] Several low-cost systems exist that use a single-camera setup, footswitches, accelerometers, gyroscopes, and inertial measurement units; however, results on the accuracy of spatial parameters are inconsistent or absent and it is questionable whether some of these systems are reliable in persons with gait deviations (e.g. forefoot contact at initial contact).[19-30]

A 2-dimensional spatiotemporal gait analysis system (SGAS) at relatively low-cost (approximately one-tenth of the price of a GAITRite® system) was developed that measures spatiotemporal gait parameters in the sagittal plane using a single camera placed perpendicular to the walkway. The camera can either be used in a stationary position, or moved manually along a parallel rail system to capture multiple strides during a single walk. The SGAS uses custom software for camera calibration and position and time measurement.[31] Individuals walk unobtrusively while their gait is recorded with the camera. To our knowledge no camera system using this calibration method has been validated for assessing spatiotemporal gait parameters.

The aim of this study was to establish the concurrent validity of the SGAS for assessing the spatiotemporal parameters of gait in healthy subjects under 4 different walking conditions: barefoot walking, shod walking, and to mimic gait deviations that may result from neurological or musculoskeletal disorders, toe walking and slow walking. Furthermore, the minimum number of footsteps needed to achieve reliable estimates of

spatiotemporal gait parameters, inter-rater and intra-rater reliability, and measurement error were determined.

Methods

Subjects

A sample of 33 healthy adults (13 men, 20 women, mean age 43 years, standard deviation (SD) 12 years) were recruited from employees, their relatives, and visitors to our rehabilitation centre through flyers posted at the centre (see Table 5.1 for subject characteristics). Individuals were eligible if they were over 18 years of age, could walk independently, and were free of musculoskeletal or neurological pathology. Data collection took place at the human movement laboratory of our centre. The study protocol was approved by the medical ethics committee of the Academic Medical Centre of the Amsterdam University Medical Centres (protocol number NL50002.018.14). All subjects provided written informed consent.

Table 5.1. Subject characteristics (n=33)

Characteristics	Mean (SD)
Age, years	43.1 (12.0)
Body height, cm	177.9 (10.5)
Body mass, kg	76.0 (14.2)
Leg length, cm	92.4 (7.1)
Foot length, cm	26.5 (1.7)
Comfortable gait speed, m/s	1.2 (0.2)
Cadence, steps per min[a]	108.8 (8.7)
Step width, cm[a]	68.2 (6.9)
Gait cycle time, s[a]	1.1 (0.1)
Stride length left leg, cm[a]	137.2 (13.6)
Stride length right leg, cm[a]	137.2 (14.0)

[a]At comfortable gait speed measured by the GAITRite® system.

Instrumentation

The SGAS consists of a high-definition 2.2-megapixel camera with 50× optical zoom (f/1.8–4.2, 16:9), sampling at 50 Hz (Panasonic Corporation, Osaka, Japan). Custom software on a Windows computer with a high-definition multimedia interface (HDMI) frame grabber was used for camera calibration, video recording, and position and time assessment (TMSi, Oldenzaal, the Netherlands). The SGAS software is available open source (https://github.com/MvanBloemendaal/SGAS). The camera was levelled and positioned on a movable tripod (camera dolly). In this study, the camera was positioned at a height of 92 cm and the perpendicular distance from a 10-m long walkway equals 360 cm (schematic representation in Supplement 5.1). The camera was used both in a stationary position (a length of 130 cm of the walkway could be captured reliably within the field of view) and as a moving camera on a 7-m long rail (dolly track) placed parallel to the walkway, over which the camera could be moved manually (Figure 5.1). An overview of the SGAS requirements and costs is presented in Supplement 5.2.

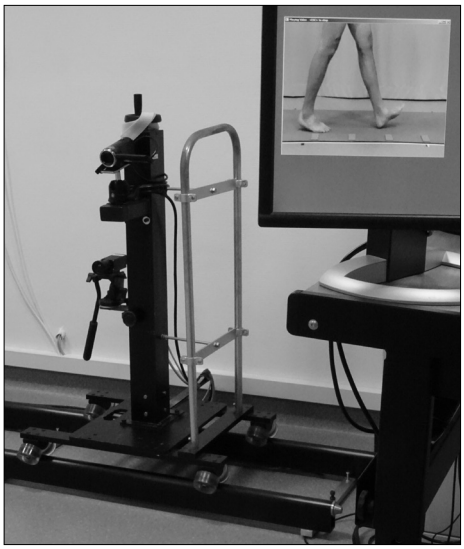
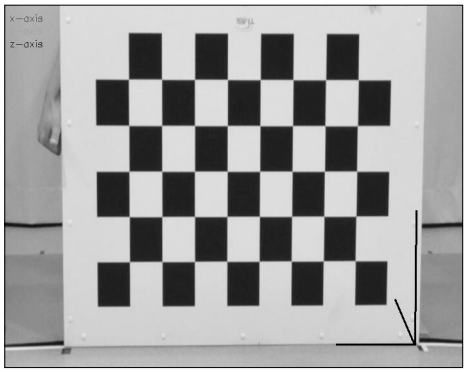


Figure 5.1. Spatiotemporal gait analysis system (SGAS): camera positioned on a movable tripod and the computer screen with the software.

Figure 5.2. Calibration of the camera for determining the projection matrix.



The SGAS measures calibrated positions on the floor of the walkway. The calibration procedure is based on the method proposed by Zhang[31]. Intrinsic camera parameters are determined from approximately 30 images of a planar 6×10 chequerboard pattern of 9-cm squares (Figure 5.2). These parameters characterize the camera's optical system. Placing this chequerboard pattern vertically in a well-defined location on the walkway sets up an orthogonal laboratory coordinate system in which the y-axis runs along the walkway, the x-axis is perpendicular to the walkway, and the z-axis points vertically upwards. The position and orientation of the camera with respect to this coordinate system are determined from a single image of the chequerboard pattern at this location. This image provides the information for the camera's extrinsic parameters. Combining the intrinsic and extrinsic parameters results in the camera's projection matrix, which describes how the coordinates of a point in the laboratory coordinate system are converted into the pixel coordinates of the camera's image plane. In the current study, the set-up and calibration process of the SGAS took approximately 10 min; calibration was repeated after assessing 8 subjects and in a clinical setting requires one calibration for the day.

The y-coordinates of an object on the floor are determined manually from the video image. On the basis of the projection matrix, the SGAS software draws a thin red line in the video image representing the projection of the line in the x-direction for a given y-coordinate in the plane z=0 (Figure 5.3). The user adjusts the y-coordinate of this line by moving the computer's mouse until the projection matches the position of the object on the floor in the image; for instance, the location of heel contact of a foot. The user reads the corresponding y-coordinate from the SGAS user interface. The time of the event is derived from the video frame rate (time resolution 0.02 s). Counting the number of frames yields the time difference between 2 events in the video recording.

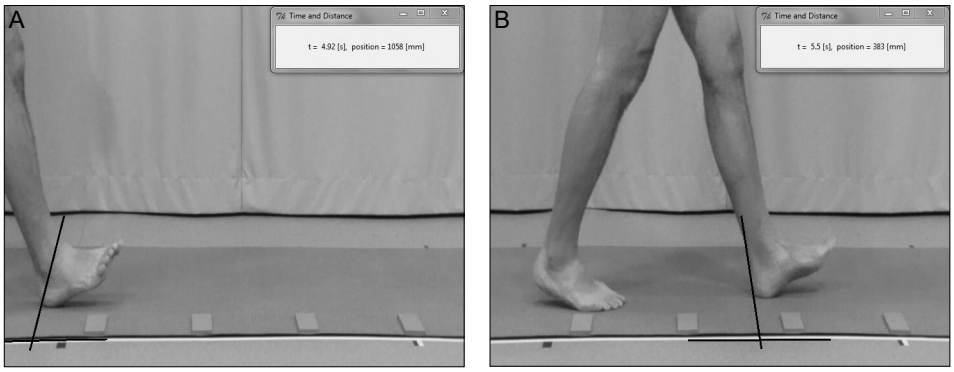


Figure 5.3. Video analysis using the spatiotemporal gait analysis system (SGAS).

Simultaneously with the SGAS, the gait of the subject was recorded with the GAITRite® system. The GAITRite® system (GAITRite® Platinum 488P, CIR Systems Inc., New York, USA) consists of a portable carpet walkway embedded with pressure-activated sensors that sample at 60 Hz. The walkway is 488 cm long and 61 cm wide and contains an active sensor area of 384×48 sensors arranged 1.27 cm from each other (centre on centre, 18,432 sensors in total).

Experimental set-up

During a 30-min test session, subjects were tested in 4 different walking conditions in a fixed order under stationary camera setup: barefoot walking at comfortable speed; barefoot walking at slow speed; barefoot toe walking at comfortable speed; and shod walking at comfortable speed wearing their own comfortable flat-soled shoes. Data collection with the SGAS and GAITRite® system was conducted by one investigator (MVB).

Ten valid gait trials, 5 in which a left and 5 in which a right footstep was visible within the 130-cm field of view, per walking condition were collected with the GAITRite® system and SGAS in a stationary position. Gait strides were collected in the given field of view by the stationary SGAS camera for the conditions of slow speed and toe walking.

In addition to the stationary camera conditions, while walking barefoot at a comfortable walking speed, 4 gait trials, including 4–8 strides per trial, were collected with the SGAS camera being moved along the walkway by the investigator.

Inter-rater reliability was assessed with 3 trained observers who were instructed in the definitions of the spatiotemporal gait parameters (Supplement 5.3) and gait analysis method. To assess intrarater reliability, one observer (MVB) assessed the same data on 2 different occasions (minimally 1 month apart). Inter-rater and intra-rater reliability were assessed for the barefoot comfortable walking condition with the stationary SGAS camera.

Data processing and analysis

The initial contact (heel or toe) and toe-off distance and timepoints during each trial were identified manually from the video images of the SGAS by 5 trained observers and were recorded in a Microsoft Excel spreadsheet format (Microsoft Corporation, Washington, USA) that was designed to automatically calculate the spatiotemporal gait parameters (https://github.com/MvanBloemendaal/SGAS). Analysed data from the SGAS and the GAITRite® system were: step length, step time, stance time, double support time, stride length, stride time, and swing time.

Statistical analysis

Concurrent validity was evaluated from the intraclass correlation coefficients model 2,1 ($ICCs_{2,1}$) using a 95% confidence interval (95% CI), and the standard error of measurement (SEM) and percentages (%SEM) were calculated from an analysis of variance. The SEM was considered small if it represented less than 5% of the weighted mean. Systematic differences between the systems were determined using paired *t*-tests. Based on the resolution of the GAITRite® system for spatial (1.27 cm) and temporal (0.02 s) parameters, differences smaller than these values were considered as measurement error. Bland-Altman repeatability coefficients (RCs) were calculated as 1.96 times the standard deviation of the difference between the 2 systems under comparison. The RC was considered small if it represented less than 8% of the weighted mean, which was the RC found between the GAITRite® system and 3-dimensional gait analysis systems.[32]

To determine the minimum number of footsteps needed to achieve an adequate level of reliability for the SGAS data, ICCs model 3,1 ($ICCs_{3,1}$) were calculated per gait parameter for 2 steps and for each incremental step (*n*) up to 10 steps. Subsequently, a coefficient of variation (CoV) was calculated between the 95% limits of agreement interval (calculated as the mean difference of *n* steps and 10 steps±1.96 times the SD of the difference between *n* steps and 10 steps) divided by the mean value for 10 steps. Data were considered reliable when this CoV was examined using ICCs (inter-rater: $ICC_{2,1}$ and intra-rater: $ICC_{3,1}$) with 95% CIs.

The following classification for the ICC was used: poor (<0.50), moderate (0.50–0.74), good (0.75–0.89), and excellent (≥0.90). An ICC with a value of 0.90 or greater and a lower limit of the 95% CI of at least 0.75 were considered as acceptable.[33] For all ICCs, the absolute agreement criterion was used. The presence of heteroscedasticity was examined through visual inspection of the Bland-Altman plots. To ensure statistical power, a sample size of at least 30 subjects was required.[34] Significance was set at $p<0.05$. Data analysis was performed using IBM SPSS Statistics 23.0 (SPSS Inc., Chicago, IL, USA).

Results

Approximately 78–98% of the collected data across walking conditions for the stationary and moving setup of the SGAS and the GAITRite® system was applicable. Most missing data came from invalid trials with the GAITRite® system due to steps outside the active sensor area and errors in the foot detection of the sensors. In total, between 256 and 322 valid trials of footsteps across conditions for the stationary and moving setup were collected from the SGAS and GAITRite® data (Table 5.2). In addition, data were collected for between 150 and 256 valid trials of strides across conditions for the moving setup and for the conditions slow gait speed and toe walking from the stationary setup of the SGAS and the GAITRite® system.

Concurrent validity and measurement error of the stationary SGAS camera

Excellent agreement for step length, step time, stance time, swing time, stride length, and stride time was found between the SGAS and the GAITRite® system in all walking conditions (ICC≥0.95 and lower limit of the 95% CIs ≥0.78; Table 5.2). Double support time showed poor agreement for the condition comfortable gait speed (ICC=0.21 and lower limit of the 95% CI=0.02), moderate agreement for the condition toe walking (ICC=0.50 and lower limit of the 95% CI=-0.06), and good agreement for the conditions of shod walking and slow gait speed (ICC≤0.83 and lower limit of the 95% CIs ≤0.75, Table 5.2). Moreover, systematic differences for double support time were found between systems for the conditions of comfortable gait speed (mean -0.05 s and SD 0.07 s), slow gait speed (mean 0.28 s and SD 0.49 s), and toe walking (mean -0.17 s and SD 0.06 s). SEM and RCs were below the respective thresholds of 5 and 8% for all spatiotemporal gait parameters (≤2.4% and ≤6.3%, respectively), except for swing time (SEM range 3.9–9.4% and RC range 10.6–19.2%) and double support time (SEM range 9.3–40.4% and RC range 24.8–95.5%; Table 5.2).

Concurrent validity and measurement error of the moving SGAS camera

Excellent agreement for step length, step time, stance time, stride length, and stride time was found between the moving SGAS camera and the GAITRite® system with barefoot walking at comfortable speed (ICC ≥0.97 and lower limit of the 95% CIs ≥0.95; Table 5.2). Paired *t*-tests revealed no differences exceeding the cut-off points of measurement error. Moderate agreement between systems was found for double support time and good agreement for swing time. SEM and RCs were below the respective thresholds of 5% and 8% for all spatiotemporal gait parameters (≤2.5% and ≤6.1%, respectively) except for double support time (SEM 10.2% and RC 25.6%).

Table 5.2. Concurrent validity and measurement error between the spatiotemporal gait analysis system (SGAS) and GAITRite® system for all conditions for 10 footsteps per subject

Spatiotemporal gait parameter	*n*	SGAS Mean (SD)	GAITRite® system Mean (SD)	Mean difference (SD)	$ICC_{2.1}$ (95% CI)	SEM	%SEM	RC	%RC
Comfortable gait speed[a]									
Step length, cm	315	66.60 (7.27)	67.58 (7.22)	-0.98 (1.10)*	0.98 (0.89–0.99)	1.05	1.6	2.16	3.2
Step time, s	315	0.57 (0.05)	0.57 (0.05)	0.00 (0.01)	0.99 (0.98–0.99)	0.01	1.1	0.02	3.0
Stance time, s	315	0.69 (0.07)	0.70 (0.08)	0.01 (0.02)*	0.97 (0.95–0.98)	0.01	2.0	0.04	5.1
Double support time, s	314	0.13 (0.03)	0.18 (0.07)	-0.05 (0.07)*	0.21 (0.02–0.37)	0.05	34.5	0.13	83.2
Shod walking[a]									
Step length, cm	322	70.33 (7.16)	71.57 (7.28)	-1.24 (1.28)*	0.97 (0.81–0.99)	1.26	1.8	2.50	3.5
Step time, s	322	0.56 (0.05)	0.56 (0.05)	0.00 (0.01)*	0.97 (0.96–0.98)	0.01	1.7	0.03	4.6
Stance time, s	322	0.69 (0.08)	0.69 (0.08)	0.00 (0.01)*	0.98 (0.98–0.99)	0.01	1.5	0.03	4.1
Double support time, s	322	0.14 (0.03)	0.13 (0.03)	0.01 (0.02)*	0.81 (0.75–0.86)	0.01	9.3	0.03	24.8
Slow gait speed[a]									
Step length, cm	290	41.21 (8.76)	41.87 (8.99)	-0.67 (0.90)*	0.99 (0.97–1.00)	0.79	1.9	1.76	4.2
Step time, s	289	2.05 (1.35)	2.05 (1.35)	-0.01 (0.05)	1.00 (1.00–1.00)	0.04	2.1	0.10	5.0
Stance time, s	289	3.12 (2.29)	3.19 (2.35)	0.08 (0.08)*	1.00 (0.99–1.00)	0.07	2.3	0.16	5.0
Double support time, s	288	1.15 (1.05)	0.87 (0.80)	0.28 (0.49)*	0.83 (0.66–0.90)	0.40	39.1	0.97	95.5
Swing time, s	210	0.90 (0.41)	0.99 (0.47)	-0.09 (0.09)*	0.96 (0.78–0.99)	0.09	9.4	0.18	19.2
Stride length, cm	210	78.12 (13.60)	79.36 (14.02)	-1.23 (1.26)*	0.99 (0.94–1.00)	1.24	1.6	2.46	3.1
Stride time, s	210	4.19 (2.49)	4.20 (2.49)	-0.01 (0.05)*	1.00 (1.00–1.00)	0	0	0.10	2.4
Toe walking[a]									
Step length, cm	276	42.81 (11.55)	43.27 (11.62)	-0.46 (1.39)*	0.99 (0.99–0.99)	1.04	2.4	2.72	6.3
Step time, s	275	0.64 (0.18)	0.64 (0.18)	-0.00 (0.02)	1.00 (1.00–1.00)	0.01	1.5	0.03	4.5
Stance time, s	274	0.83 (0.26)	0.83 (0.27)	0.01 (0.02)*	1.00 (1.00–1.00)	0.02	1.8	0.04	4.9
Double support time, s	274	0.19 (0.10)	0.36 (0.16)	-0.17 (0.06)*	0.50 (-0.06–0.82)	0.11	40.4	0.12	44.1
Swing time, s	151	0.43 (0.07)	0.44 (0.08)	-0.01 (0.02)*	0.95 (0.93–0.96)	0.02	3.9	0.05	10.6
Stride length, cm	150	80.88 (18.96)	81.87 (19.04)	-1.01 (1.33)*	1.00 (0.99–1.00)	1.20	1.5	2.61	3.2
Stride time, s	151	1.28 (0.36)	1.28 (0.36)	-0.00 (0.01)	1.00 (1.00–1.00)	0.01	0.9	0.03	2.1
Comfortable gait speed by the moving SGAS camera									
Step length, cm	256	69.88 (6.56)	69.94 (6.53)	-0.06 (0.85)	0.99 (0.99–0.99)	0.59	0.8	1.67	2.4
Step time, s	259	0.52 (0.04)	0.53 (0.04)	-0.00 (0.01)	0.97 (0.96–0.98)	0.01	1.4	0.02	4.0
Stance time, s	258	0.64 (0.06)	0.65 (0.06)	0.01 (0.01)*	0.98 (0.95–0.99)	0.01	1.5	0.02	3.6
Double support time, s	258	0.13 (0.03)	0.12 (0.02)	0.01 (0.02)*	0.72 (0.55–0.82)	0.01	10.2	0.03	25.6
Swing time, s	256	0.40 (0.03)	0.41 (0.03)	-0.01 (0.01)*	0.88 (0.74–0.93)	0.01	2.5	0.02	6.1
Stride length, cm	256	139.74 (12.76)	139.84 (12.75)	-0.10 (1.25)	1.00 (0.98–1.00)	0.90	0.7	2.45	1.8
Stride time, s	256	1.05 (0.08)	1.05 (0.08)	-0.00 (0.01)	0.99 (0.99–0.99)	0.08	0.7	0.02	1.9

*$p<0.05$. [a]Stationary SGAS camera. *n*: number of trials (depending on valid trials of the SGAS and GAITRite® system for all 33 subjects); SD: standard deviation; ICC: intraclass correlation coefficient; CI: confidence interval; SEM: standard error of measurement; %SEM: standard error of measurement as percentage of the weighted mean; RC: repeatability coefficient; %RC: repeatability coefficient as percentage of the weighted mean.

Minimum number of footsteps needed for adequate reliability

Ten valid trials of footsteps were available for 25 subjects. Two footsteps were required to obtain excellent reliability scores (ICC>0.90) for all 4 assessable spatiotemporal gait parameters for barefoot comfortable walking with the stationary SGAS setup (Table 5.3). The CoV decreased gradually when averaging more footsteps. Four footsteps were required to reach a CoV below 10% for step length, step time, and stance time. The Bland-Altman plots showed no heteroscedasticity (Figure 5.4). For double support time, 8 footsteps were required. For the shod walking condition, similar results were found. The sample sizes of the toe walking and slow gait speed conditions were too small, considering that there were fewer than 10 valid trials of footsteps per subject (sample sizes of 10 and 15 subjects, respectively).

The minimum number of footsteps needed for adequate reliability during comfortable barefoot walking by the moving SGAS camera in 30 subjects were 3 footsteps for step length, step time, and stance time and 7 footsteps for double support time.

Inter- and intra-rater reliability

For assessment of the inter- and intra-rater reliability, 304–316 trials were used. Step length, step time, and stance time values had excellent agreement between the 3 observers (ICC≥0.94 and lower limit of the 95% CIs ≥0.86). Inter-rater agreement on double support time was moderate (ICC 0.68 and 95% CI 0.48–0.79). Intra-rater reliability was excellent for step length, step time, and stance time (ICC≥0.98 and lower limit of the 95% CIs ≥0.97), and good for double support time (ICC 0.84 and 95% CI 0.80–0.87).

Discussion

This study found that the SGAS is a valid and reliable system to assess step length, step time, stance time, stride length, and stride time under different walking conditions. The stationary, as well as the moving, camera set-up can be used to determine these spatiotemporal gait parameters. However, validity could not be confirmed for double support time and swing time. A minimum of 4 footsteps was needed to obtain a reliable assessment of step length, step time, and stance time with the SGAS. Inter- and intra-rater reliability were confirmed for step length, step time, and stance time.

There is a need for low-cost and portable gait analysis technology in clinical settings. Such technology needs to be assessed for validity and reliability in assessing spatiotemporal gait parameters, such as in the current study using a 1-camera method. One other study using a 1-camera system examined the validity between this system and a reference 3-dimensional motion capture system.[20] They found differences in accuracy between the 2 systems that were similar compared with the current study for the temporal parameters. However, they found larger differences between the system and the

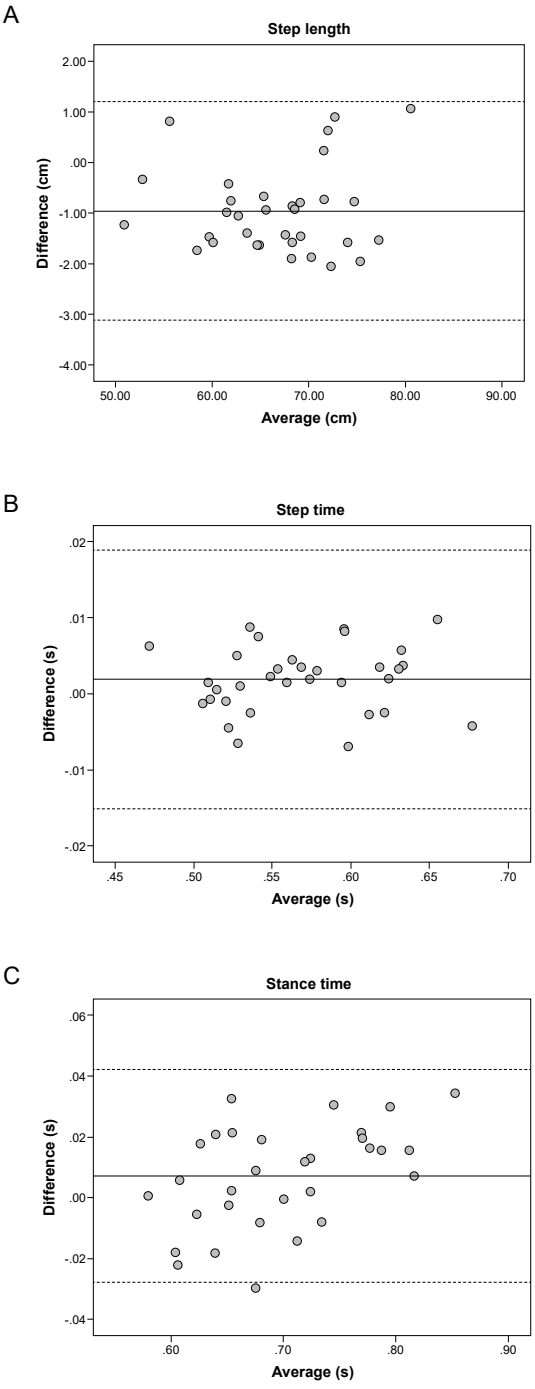


Figure 5.4. Bland-Altman plots of step length, step time, and stance time for 4 footsteps averaged with the stationary spatiotemporal gait analysis system (SGAS).

Table 5.3. Number of footstep repetitions for reliable spatiotemporal gait analysis system (SGAS) data for the barefoot comfortable gait speed condition by the stationary placed camera (n=25)

Footsteps, *n*	Step length $ICC_{3,1}$ (95% CI) [%CoV]	Step time $ICC_{3,1}$ (95% CI) [%CoV]	Stance time $ICC_{3,1}$ (95% CI) [%CoV]	Double support time $ICC_{3,1}$ (95% CI) [%CoV]
1	0.87 (0.73–0.94) [18.7]	0.86 (0.70–0.93) [21.4]	0.87 (0.73–0.94) [24.0]	0.85 (0.70–0.93) [49.6]
2	0.97 (0.93–0.99) [12.8]	0.96 (0.91–0.98) [14.4]	0.96 (0.92–0.98) [17.0]	0.97 (0.92–0.98) [33.5]
3	0.98 (0.95–0.99) [10.4]	0.98 (0.95–0.99) [10.3]	0.98 (0.94–0.99) [13.0]	0.97 (0.94–0.99) [30.8]
4	0.99 (0.97–1.00) [7.4]	0.99 (0.98–1.00) [7.5]	0.99 (0.98–1.00) [8.7]	0.99 (0.97–1.00) [19.6]
5	0.99 (0.98–1.00) [6.2]	0.99 (0.98–1.00) [5.9]	0.99 (0.98–1.00) [7.2]	0.99 (0.98–1.00) [17.6]
6	1.00 (0.99–1.00) [5.1]	1.00 (0.99–1.00) [4.8]	1.00 (0.99–1.00) [5.7]	0.99 (0.99–1.00) [13.9]
7	1.00 (1.00–1.00) [3.5]	1.00 (0.99–1.00) [4.0]	1.00 (0.99–1.00) [4.6]	1.00 (0.99–1.00) [11.2]
8	1.00 (1.00–1.00) [2.6]	1.00 (1.00–1.00) [2.6]	1.00 (1.00–1.00) [3.0]	1.00 (1.00–1.00) [7.1]
9	1.00 (1.00–1.00) [2.3]	1.00 (1.00–1.00) [1.3]	1.00 (1.00–1.00) [1.7]	1.00 (1.00–1.00) [5.0]

ICC: intraclass correlation coefficient; CI: confidence interval; %CoV: coefficient of variation (the 95% limits of agreement interval for *n* versus 10 footsteps divided by the mean value for 10 footsteps) as percentage.

reference for the spatial parameters compared with our study, which may, among other possible explanations, be due to the choice of reference system. Results on reliability and measurement error were not reported in that study. Furthermore, they examined the validity for different gait speed conditions with the subjects wearing ankle socks, but not for the conditions of toe walking or shod walking. The Microsoft Kinect v2, which is a camera system extracting data from 3-dimensional skeletal modelling, has been shown to provide valid results for temporal parameters. Although results on accuracy for spatial parameters were inconsistent between studies,[19,21-24] one study showed an ICC of 0.76 for step length (95% CI -0.17 to 0.95) and an absolute and relative error of 10 cm (SD 5 cm).[21] Other low-cost alternatives using footswitches, accelerometers, gyroscopes, and inertial measurement units have been shown to be accurate in measuring temporal gait parameters, but are currently either unable or inaccurate to measure spatial parameters.[25-30] Moreover, the advantage of a camera system over these methods is that video images of the person are obtained, which can be used for clinical assessment of gait pathology.

The SGAS is a feasible, easy-to-use measurement instrument for clinical practice and research purposes. In the current study, position and time assessment to calculate the spatiotemporal gait parameters from the SGAS user interface was a manual process. For experienced observers, position and time assessment for 10 trials in one walking condition took approximately 10–15 min. The observers noted that the video capture with time resolution of 0.02 s regularly missed the exact moment of initial contact or toe off, complicating the assessment. However, this did not compromise the reliability, since the results show that accurate data can be obtained with a 50 Hz sampling rate. The stationary camera set-up can be used in all settings, but is restricted by the field of view. In this study, the chosen field of view was 130 cm, to provide good spatial resolution for accuracy, but at the expense of being able to assess full strides. The use of a moving camera set-up solves this problem and, additionally, requires less effort from persons, as multiple steps are analysed in a single trial. A moving SGAS camera does, however, require a rail placed parallel to the walkway and a steady tripod on wheels. Recordings from the SGAS can be combined with other gait recordings (e.g. electromyography and force plate).

In this study, double support time and swing time could not be assessed in a valid and reliable way with the SGAS using the GAITRite® system as a reference. Whether this is a limitation of the SGAS or of the reference system is not fully clear, as no study on the measurement properties of the GAITRite® system has assessed how valid this system is in assessing double support time,[15,16,32,35-38] and only one study described swing time, but results on measurement error were not reported.[16] In support of our findings, 2 other studies found moderate levels of agreement between the GAITRite® system and low-cost, portable systems for assessing double support time and swing time.[26,39] Perhaps the low time resolution of these systems (i.e. 50 Hz) could be an explanation for these findings, as double support and swing time are short events in the gait cycle. A camera with a higher

sampling rate (e.g. 100 Hz) could be applied, but a disadvantage is that the size of the video data will substantially increase.

The current study has some limitations. The calculated minimum number of footsteps needed to achieve an adequate level of reliability for the SGAS data may not be generalizable to individuals with gait deviations. These individuals often show larger step variability and may show rotations in the transverse plane, such as foot inward rotation, which may lead to inaccuracies in measurements in the sagittal plane. Future research on this topic should include subjects with gait deviations and examine more than 10 trials of footsteps and strides, as recommended by other studies.[16,40] A second limitation concerned an error in the experimental set-up, where calibration of the SGAS was carried out on the floor and not on the GAITRite® carpet, which is 0.32 cm above the floor. This error has most likely influenced the differences found in the spatial parameters between the SGAS and the GAITRite® system (significant mean differences for step length of 0.06–1.24 cm). Finally, while data processing is not considered time-consuming, efficiency may be improved by automated processing. For example, in determining initial contact and toe off, which will also enhance accuracy and feasibility.

In conclusion, the SGAS is a valid and reliable system for assessing step length, step time, stance time, stride length, and stride time in different walking conditions and with both stationary and moving camera set-up. The validity of the SGAS for the assessment of double support time and swing time needs further investigation, preferably using a 3-dimensional gait analysis system as reference. Moreover, future research should validate the SGAS in subjects with gait deviations. A minimum of 4 footsteps is recommended for adequate reliability in each of the parameters tested, with a stationary camera.

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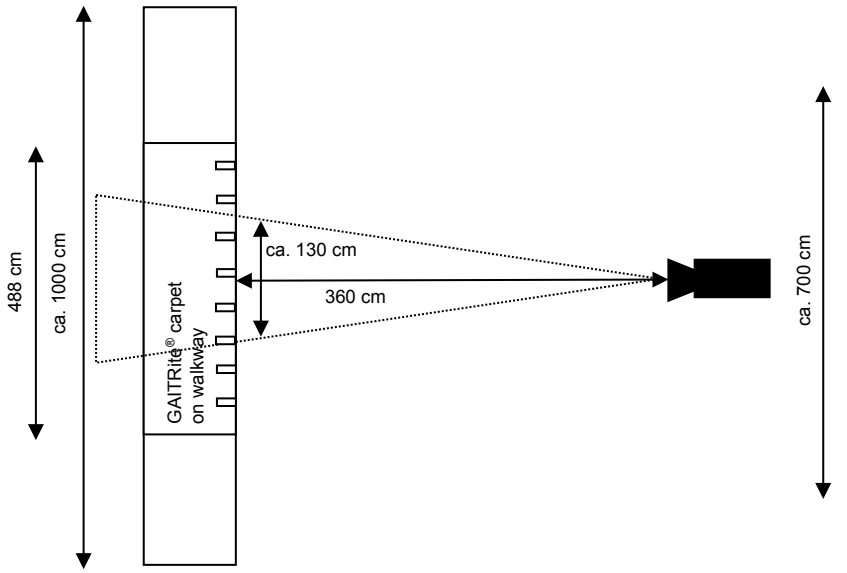
Supplement 5.1.

Schematic representation of the experimental set-up with the camera fixed at 92 cm height and movable along a parallel track.



Supplement 5.2.

Overview of spatiotemporal gait analysis system (SGAS) requirements and costs.

Software

The SGAS software, consisting of 3 parts (i.e. camera calibration, video recording, and position and time assessment software), and Excel data forms for data collection and calculation of the spatiotemporal gait parameters are available open source at: https://github.com/MvanBloemendaal/SGAS.

Hardware

The hardware used in the study, containing a camera (high-definition 2.2-megapixel camera with 50× optical zoom [f/1.8–4.2, 16:9], sampling at 50 Hz), 10-m long HDMI cable (length depends on stationary or moving setup), and HDMI frame grabber, cost approximately €1,700. Furthermore, a Windows computer with an input for the HDMI frame grabber (or with an integrated HDMI frame grabber) is required.

Materials

A planar 6 × 10 chequerboard with a pattern of 9-cm squares (Figure 5.2 in the main text shows the chequerboard used in the study). This can be made of flat material such as wood or plastic (it should not be too heavy).

Stationary setup

A tripod for stationary setup is available, from €15.

Stationary and moving setup

A 7-m long dolly track (the length used in the study) and camera dolly are available, from approximately €700. A comparable version with the one used in the study, is available for approximately €2,500–3,000.

Supplement 5.3.

Definitions of spatiotemporal gait parameters used in the analysis.

Spatiotemporal gait parameter	Definition spatiotemporal gait analysis system	Definition GAITRite® system
Step length, cm	Distance from the most distal point of the heel strike of the first foot (0% of the gait cycle) to the most distal point of the heel strike of the opposite foot (0% of the next gait cycle)	Line of progression from the heel centre of the current footprint to the heel centre of the previous footprint on the opposite foot
Step length at toe walking, cm	Distance from the most distal point of the hallux of the first foot completely on the ground to the most distal point of the hallux of the opposite foot completely on the ground	Line of progression from the toe base of the current footprint to the toe base of the previous footprint on the opposite foot (gait pattern toe base measurement)
Step time, s	Time elapsed between the first moment of contact with the ground of the first foot (0% of the gait cycle) to the first moment of contact with the ground of the opposite foot (0% of the next gait cycle)	Time elapsed from first contact of 1 foot to first contact of the opposite foot
Stance time, s	Time elapsed between the first moment of contact with the ground (initial contact) to the last moment of contact with the ground of 1 foot (toe off)	Time elapsed between the first contact and the last contact of 2 consecutive footfalls on the same foot
Double support time, s	Time elapsed between the first moment of both feet in contact with the ground to the very last moment of contact of 1 of both feet with the ground (toe off)	From opposite footfall heel strike to support footfall toe-off (unloading/terminal double support)
Swing time, s	Time elapsed between the last moment of contact with the ground (toe off) to the first moment of contact with the ground (initial contact) of 1 foot	Time elapsed between the last contact of the current footfall to the first contact of the next footfall on the same foot
Stride length, cm	Distance from the most distal point of the heel strike of the first foot to the most distal point of the next heel strike of the same foot	Line of progression between the heel points of 2 consecutive footprints of the same foot
Stride time, s	Time elapsed between the first moment of contact with the ground of the first foot to the next first moment of contact with the ground of the same foot	Time elapsed between the first contacts of 2 consecutive footfalls of the same foot

Chapter 6

Gait training assisted by multi-channel functional electrical stimulation early after stroke: study protocol for a randomized controlled trial

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Trials
2016; 17:477

Abstract

Background. Many stroke survivors suffer from paresis of lower limb muscles, resulting in compensatory gait patterns characterised by asymmetries in spatial and temporal parameters and reduced walking capacity. Functional electrical stimulation has been used to improve walking capacity, but evidence is mostly limited to the orthotic effects of peroneal functional electrical stimulation in the chronic phase after stroke. The aim of this study is to investigate the therapeutic effects of up to 10 weeks of multi-channel functional electrical stimulation (MFES)-assisted gait training on the restoration of spatiotemporal gait symmetry and walking capacity in subacute stroke patients.

Methods. In a proof-of-principle study with a randomised controlled design, 40 adult patients with walking deficits who are admitted for inpatient rehabilitation within 31 days since the onset of stroke are randomised to either MFES-assisted gait training or conventional gait training. Gait training is delivered in 30-minute sessions each workday for up to 10 weeks. The step length symmetry ratio is the primary outcome. Blinded assessors conduct outcome assessments at baseline, every 2 weeks during the intervention period, immediately post intervention and at 3-month follow-up.

Discussion. This study aims to provide preliminary evidence for the feasibility and effectiveness of MFES-assisted gait rehabilitation early after stroke. Results will inform the design of a larger multi-centre trial.

Background

Regaining independent gait is considered one of the primary goals in stroke rehabilitation.[1-3] In the early phase after stroke, the musculature of the affected side is often paretic or even paralytic. As a consequence, compensatory gait patterns characterised by asymmetries in spatial and temporal parameters may arise that tend to be persistent, even in patients who show substantial restoration of paretic leg motor control, perhaps due to mechanisms related to 'learned non-use' as has been described for the upper extremity.[4] These compensatory gait patterns are less energy-efficient and may negatively affect balance control leading to an increased risk of falls and injury as well as to limitations in functional mobility.[5-8] Furthermore, they may cause secondary complications, such as muscle shortening and joint deformation.[6] Restoration of gait symmetry can be accomplished by motor relearning and neuroplasticity, for which highly intensive, repetitive and task-specific training is essential in the early rehabilitation phase after stroke.[9,10] The use of functional electrical stimulation (FES) timed to the gait cycle in the early phase after stroke may improve gait symmetry by enhancing neuroplasticity, preventing secondary complications, and by supporting the acquisition of an adequate compensatory strategy. Although the orthotic effects of peroneal FES (PFES) have been established, the therapeutic effect of PFES in the subacute phase has been scarcely investigated.[11-19] Furthermore, PFES assists the ankle dorsiflexion movement only during the swing phase and early stance phase of gait and does not support the more proximal movements of the lower limb. Several studies have shown that strength and range of motion of the knee flexors and extensors are associated with gait performance.[20-22] Thus, multi-channel FES (MFES) of the distal and proximal parts of the lower limb may be more effective in normalising the gait pattern by compensating for thigh and dorsiflexor muscle weakness. There is preliminary evidence of a positive therapeutic effect of MFES in early stroke rehabilitation on balance control and mobility.[23-25] However, it remains unclear whether MFES is effective for the restoration of gait symmetry. Furthermore, it remains unclear whether it is feasible to implement MFES in functional gait training including pre-gait activities. Due to the limited evidence of MFES-assisted gait training during early stroke rehabilitation we designed a proof-of-principle study. The aim of this study is to examine the feasibility and preliminary efficacy of MFES-assisted gait training on gait symmetry and walking capacity in patients in the subacute phase after stroke during their inpatient rehabilitation. We hypothesise that MFES-assisted gait training for maximally 10 weeks in the early phase after stroke is feasible and improves the step length symmetry compared to conventional gait training. In this paper we describe the protocol of our study according to the SPIRIT guidelines (Trials 2016; 17:477, Additional file 1).

Methods

Design

A prospective, assessor-blinded, single-centre, proof-of principle study with a randomised controlled two-armed parallel design is being conducted. Forty participants with gait impairments in the subacute phase after stroke who are referred for inpatient rehabilitation are randomly assigned in a 1:1 ratio to either an intervention group, receiving MFES-assisted gait training, or a control group, receiving gait training as usual. The intervention period lasts 10 weeks or until discharge from inpatient rehabilitation, whichever is sooner. Outcomes will be assessed every 2 weeks during the 10-week intervention period as well as after a 3-month follow-up period (Figure 6.1).

Ethics

The study protocol has been approved by the Medical Ethics Committee (MEC) of the Academic Medical Centre Amsterdam (protocol number NL50002.018.14). Any changes to the study protocol or study procedures will be reviewed and approved by the MEC and communicated to relevant parties. A Dutch rehabilitation centre (Merem Rehabilitation Centre De Trappenberg in Huizen) granted approval to include and train participants. The study has been registered at the Netherlands Trial Register (number NTR4762, registered 28 August 2014). Additional file 2 (Trials 2016; 17:477) provides an overview of the trial registration data.

Participants

Participants are recruited at the rehabilitation centre. All stroke survivors admitted for inpatient rehabilitation are screened for eligibility by their physiatrist. Inclusion criteria are: (1) a clinical diagnosis of stroke (diagnostic criteria according to the World Health Organization definition);[26] (2) within 31 days since stroke onset; (3) age between 18 and 80 years; (4) indication for gait training (according to the treating physiatrist); (5) sufficient capacity to stand between parallel bars with or without physical assistance and able to walk with aids and physical assistance from one physical therapist (Functional Ambulation Categories [FAC] score ≥1); and (6) passive range of motion (PROM) upon ankle dorsiflexion ≥0° with full knee extension. Exclusion criteria are: (1) subarachnoid haemorrhage or stroke in the cerebellum or brain stem; (2) severe spasticity of the knee or ankle flexors or extensors (i.e., Modified Ashworth Scale [MAS] ≥ 3); (3) pre-existing lower limb deficits or any other medical co-morbidities that might significantly interfere with gait (indicated by a self-reported maximum walking distance <300 meter or walking duration <6 minutes walking pre stroke); (4) severe cognitive problems or aphasia leading to severely impaired comprehension of test instructions; (5) medical conditions that might lead to inability to comply with the study protocol (e.g., congestive heart failure, chemotherapy, uncontrolled epilepsy, pregnancy, depression or psychotic disorder, etc.);

	STUDY PERIOD							
	Enrolment	Allocation	Post-allocation					Close-out
TIMEPOINT	$-t_1$	t_0	$t_{1.1}$	$t_{1.2}$	$t_{1.3}$	$t_{1.4}$	t_2	t_3
ENROLMENT:								
Eligibility screen	x							
Informed consent	x							
Allocation		x						
INTERVENTIONS:								
MFES in usual care (intervention group)			◆	◆	◆	◆	◆	
Control group (usual care)			◆	◆	◆	◆	◆	
ASSESSMENTS:								
Efficacy (primary and secondary outcome assessments)								
Spatiotemporal gait analysis system		x			x		x	x
Two-dimensional gait analysis		x			x		x	x
Three-dimensional gait analysis							x	
Functional Gait Assessment		x	x	x	x	x	x	x
Functional Ambulation Categories	x	x	x	x	x	x	x	x
Comfortable Ten Meter Walking Test		x	x	x	x	x	x	x
Patient subjective gait recovery score (percentage)		x	x	x	x	x	x	x
Berg Balance Scale		x			x		x	x
Falls Efficacy Scale I								x
Feasibility								
Patient satisfaction with gait training (1-item numeric rating scale)					x		x	
Patient satisfaction with the MFES-device (questionnaire)							x	
Patient characteristics (body functions lower limb)								
Motricity Index		x			x		x	x
Brunnström Fugl-Meyer Assessment		x			x		x	x
Passive Range of Motion		x			x		x	x
Erasmus Medical Centre Modified Nottingham Sensory Assessment		x			x		x	x
Modified Ashworth Scale I		x			x		x	x

$-t_1$, enrolment week 0; t_0, allocation and baseline week 0; t_1, every two weeks during intervention; t_2, post intervention (maximally week 10); t_3, three months follow-up; MFES, multi-channel functional electrical stimulation

Figure 6.1. Schedule of enrolment, interventions and assessments.

(6) demand-type cardiac pacemaker, defibrillator or electrical implant; (7) metallic implant at the affected lower limb; or (8) present or suspected cancerous lesion at the affected lower limb. Potentially eligible participants receive verbal and detailed written information (Trials 2016; 17:477, Additional file 3) about the study and are invited to participate. In case of willingness to participate, an intake assessment is performed by a researcher who explains the purpose and procedures of the study and asks for informed consent. The following demographics are recorded for each participant: gender, date of birth, body length, body mass, type of stroke, location of stroke (left, right or both), hemiplegic side (left or right), date of stroke, neglect (tactile and visual present or not), relevant co-morbidities,

medication and FAC. Furthermore, the following sensorimotor characteristics of both lower limbs are recorded for each participant: Motricity Index (muscle strength),[27] Brunnström Fugl-Meyer Assessment (motor selectivity),[28] and specific parts of the Erasmus Medical Centre Modified Nottingham Sensory Assessment (tactile and proprioceptive sensation),[29] MAS (muscle tone),[30,31] and passive range of motion at the hip, knee and ankle (PROM). Strategies for patient retention include sending newsletters, accommodating their schedules when planning follow-up visits, sending reminders of upcoming visits, and providing transport support.

Randomisation and blinding

Concealed randomisation and allocation is effectuated by an assigned researcher (AB), who is not involved in any patient contact, using a computerised randomisation system. Randomisation takes place stratified by functional walking capacity (dependent gait [FAC 1–2] versus independent gait [FAC 3–5]). Outcome assessors are kept blinded to allocation of the participants during all assessments. Participants are instructed not to reveal their group allocation or therapy content to the assessors. Data will be analysed by an independent statistician. Randomisation will be concealed to the primary researcher until data analysis has been completed.

Interventions

Control group. Participants in the control group will receive regular gait training by a physical therapist and/or movement therapist depending on their needs. Typically, per week, three to eight 30-minute sessions of gait-oriented physical therapy are given on five working days for 6 to 12 weeks. This ‘usual care’ may include individual gait training, gait training in groups, fitness training, sports, and hydrotherapy. Walking aids, orthoses, orthopaedic shoes and medication may all be used, but not lower limb FES. Participants will not be restricted in their activities. Therapists are instructed to document characteristics of the gait training (duration, frequency and content) for each participant in weekly logs.

Intervention group. Participants in the intervention group receive the same amount of gait-oriented physical therapy, but gait training is assisted by MFES. Per week, MFES is delivered during one 30-minute session on five working days up to 10 weeks. Physical therapists and movement therapists specifically trained in the use of MFES carry out the gait training. They are instructed to document characteristics of the gait training (duration, frequency, content and intensity of MFES) for each participant in weekly logs. During an initial adaptation period of 4 days, the duration of MFES is gradually increased from 15 minutes (day 1) to 30 minutes (day 4). Thereafter, participants receive 30-minute session of MFES-assisted gait training on each workday.

Figure 6.2. The functional electrical stimulation device including two cuffs, a foot switch, and a control unit.

Multi-channel functional electrical stimulation device

The MFES device used in this study (NESS L300™ Plus, Bioness, Valencia, CA, USA; CE 0473) delivers electrical pulses during gait to muscles in the affected leg to promote ankle dorsiflexion in combination with knee flexion or extension. The device consists of two cuffs (lower leg and thigh), a foot switch, and a wireless control unit that activates the system by radio frequency signals (Figure 6.2). In each cuff two cotton electrodes and a stimulation unit are embedded. The electrodes of the lower leg cuff are located over the common peroneal nerve and the tibialis anterior muscle to elicit ankle dorsiflexion. The electrodes of the thigh cuff are positioned over the vastus medialis muscle to promote knee extension or over the biceps femoris brevis muscle to promote knee flexion. With this configuration, either paretic muscles can be stimulated or spastic muscles antagonised. Figure 6.3 illustrates some examples of positioning of the thigh cuff and timing of the upper leg stimulation expressed as percentage of the gait cycle.[32] Authorised clinicians are specially trained to fit and set the MFES device. They fit the device at baseline and evaluate the settings of the device every two-and-a-half weeks. A force-sensitive resistor in the foot switch detects the force under the foot. A dynamic gait-tracking algorithm is used to detect whether the foot is on the ground (e.g., initial contact) or in the air (e.g., heel off) by analysing the foot pressure. Average stance and swing phases are calculated by the system and data is transmitted by radio signals to the stimulation unit allowing for the synchronisation of the stimulation in accordance with the timing of gait events (gait mode). During the fitting process, the clinician sets the stimulation parameters

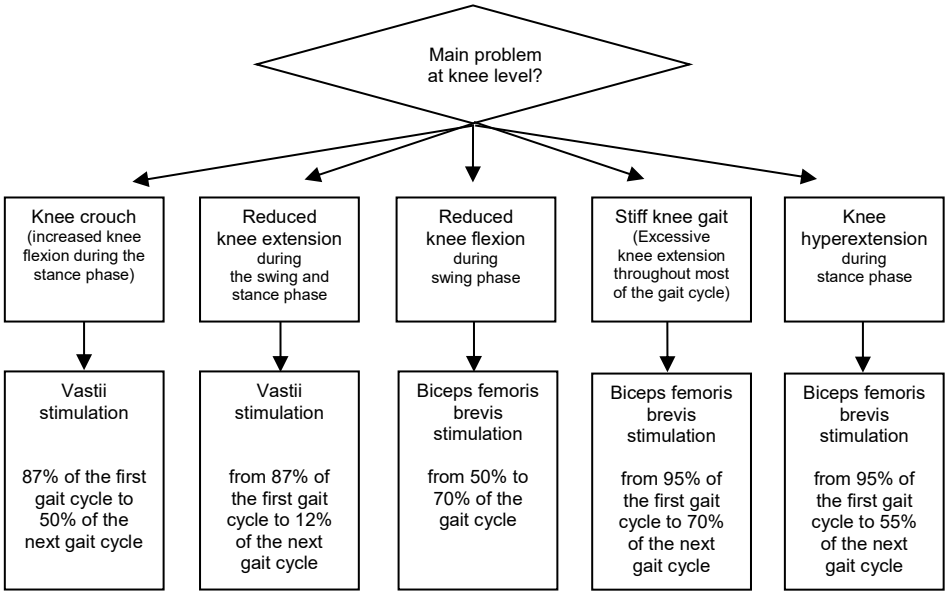

Figure 6.3. Examples of thigh cuff muscle activation during the gait cycle.

(intensity level, phase duration, pulse rate, waveform and maximum duration of stimulation, ramp up, extension and ramp down) for the gait mode with a handheld computer (personal digital assistant; PDA). The peroneal stimulation starts at 'heel off' and terminates at 'heel contact'. Stimulation can be extended beyond heel contact to control the first rocker. The thigh stimulation – biceps femoris brevis or vastus muscles – can start and end once or twice at any segment in the gait cycle, which is determined by the clinician. Participants who cannot walk without personal assistance receive MFES treatment in the NESS L300™ Plus clinician mode (pre-gait and balance training) and gait mode (gait training) during individual physical therapy. The clinician mode is used to manually start and stop stimulation in the thigh and lower leg unit simultaneously. The clinician mode uses the stimulation parameters set for gait mode.

Outcome measures

Primary outcome. The primary outcome to determine efficacy of MFES-assisted gait training is the step length symmetry ratio. Step length during comfortable gait is measured with a spatiotemporal gait analysis system (SGAS) using a laterally placed camera (Panasonic HC-V550 High Definition camera 50 Hertz; Panasonic, Osaka, Japan) and discrete linear transform matrix software designed for this study. Participants walk at comfortable walking speed along a 10-metre walkway until three valid gait trials are collected in which each foot lands within the 1300-millimetre-wide video frame for both sides. The primary condition is walking without shoes and orthosis with minimal use of walking aids. The symmetry ratio is calculated as the difference between the step length of the affected and non-affected leg divided by the mean of the step length of both legs.

Secondary outcomes. The SGAS is also used to examine other spatiotemporal parameters (step length, stride length, cadence, stance time symmetry ratio, double support time, and swing/stance time symmetry ratio) for two conditions (walking with and without shoes and orthoses). Furthermore, sagittal and frontal plane video (Basler Scout GigE; Basler AG, Ahrensburg, Germany), electromyography (Mobita and Porti 7 8bt; TMSi, Oldenzaal, the Netherlands) and force plate recordings (OR6-7; AMTI, Watertown, MA, USA) are used to collect kinematic, electromyographic and kinetic data, respectively. One valid gait trial is collected for different conditions (walking with and without shoes, orthoses and walking aids). In addition, at the end of the intervention period, a full three-dimensional gait analysis is performed with an 8-camera VICON MX1.3 motion capture system operating at a sample rate of 100 Hertz (VICON, Oxford, United Kingdom) with two force plates in series recording at 1000 Hertz (OR6-7; AMTI, Watertown, MA, USA) positioned along a 12-metre walkway. Three valid gait trials are collected to register gait width and other kinematic and kinetic parameters that cannot be determined with the SGAS. Walking capacity is assessed with the Functional Gait Assessment (FGA), the FAC and the 10-Meter Walk Test (10MWT), all validated measurement instruments in the stroke population.[33] The FGA is a 10-item test to assess functional gait activities. The FAC is an instrument for categorising gait (in)dependency from 'no ability to walk or with the help of two or more persons' (FAC 0) to the 'ability to walk independently' (FAC 5). The 10MWT assesses comfortable and maximum walking speed. In this study, only comfortable walking speed will be recorded. Walking capacity is also assessed by a subjective walking capacity recovery score. During each visit the participant is asked to score his or her recovery of walking capacity since the onset of stroke by giving a percentage between 0% ('no recovery') and 100% ('full recovery'). Balance control is assessed with the Berg Balance Scale[34-36] and fear of falling with the Falls Efficacy Scale I (FES-I).[37]

Feasibility

Feasibility of the intervention is evaluated on the basis of compliance with the MFES-assisted gait training and patient satisfaction with this type of training using the MFES device. The following criteria are used: (1) MFES-assisted gait training took place during ≥75% of all therapy sessions; and (2) patient satisfaction with MFES-assisted gait training was ≥7 on a numeric rating scale from 0 ('most unsatisfied') to 10 ('most satisfied') assessed at the end of the intervention period. Patient satisfaction with the MFES device is evaluated by a questionnaire designed for this study.

Sample size

Due to lack of data on effect size, sample size is based on the feasibility of recruitment in one centre with an approximate yearly admission rate of 80 stroke survivors. Using an inclusion period of 3 years and estimating that 25% of the patients are eligible and willing to participate, the sample size is set at 40 participants (20 in each group).

Data management and statistical analysis

Data entry takes place by digital and paper case report forms. Personal information of the participants is treated confidentially. Every participant receives an identification number. This number is used on all forms so that no names or other personal information have to be used. Data is saved in a locked cabinet in a locked office and stored digitally in a trial master file for the duration of 15 years. Data quality is guaranteed by random checks of the research database and range checks for data values.

Descriptive statistics. Patient characteristics will be described using means, standard deviations, medians, and interquartile ranges (dependent on whether data is normally distributed or not) and percentages. Group comparisons at baseline will be performed with Student's *t* tests, Mann-Whitney *U* tests and χ^2 tests where appropriate.

Primary and secondary analysis. Primary efficacy analysis will be performed on an intention-to-treat basis. In addition, per protocol analyses will be performed. A linear mixed model for repeated measures will be used to analyse differences in the primary outcome and secondary outcomes. A squared time variable will be included to test for a curvilinear recovery curve. The interaction of time by intervention (MFES versus control) assesses whether the slopes of the recovery curves differ between groups. In these analyses both the intercept and the time variable are included as random effects. Group comparisons at the end of the intervention period for the three-dimensional gait analysis parameters and FES-I will be performed with Student's *t* tests. To assess feasibility of the intervention, the proportion of participants in the intervention group who are compliant with the gait training and who scored ≥7 on the numeric rating scale will be determined. Patient satisfaction with the MFES device will be described. In all analyses, statistical uncertainty will be expressed by means of 95% confidence intervals. Significance will be set at $p<0.05$.

Monitoring and quality assurance

Internal monitoring of the conduct of the study is performed once a year by researchers of the Merem Rehabilitation Centre De Trappenberg and the Academic Medical Centre Amsterdam. The completeness, accuracy, consistency, and procedures are checked according to the monitoring plan. Adverse events (AEs) of the individual participants are reported in the period from signing informed consent (introduction meeting) until the last follow-up meeting. All AEs reported spontaneously by the participant or observed by the primary researcher or staff are recorded. All AEs are followed until they have abated or a stable situation has been reached. Depending on the event, follow-up may require additional tests or medical procedures as indicated, and/or referral to the general physician or a medical specialist. Serious AEs (SAEs) are reported up to the end of study. The sponsor reports the SAEs to the MEC within 15 days after the sponsor has first knowledge of the SAE. SAEs that result in death or appear to be life threatening are reported expedited,

i.e. not later than 7 days after the primary researcher has obtained first knowledge of the adverse event. The primary researcher reports the progress of the trial once a year to the MEC.

Dissemination policy

Trial results are communicated to participants, healthcare professionals, the public, and other relevant groups via newsletters and (inter)national, peer-reviewed journals (Medline database). The results will be presented at relevant (inter)national conferences in rehabilitation and neurology. Furthermore, results will be published on websites of patient societies.

Discussion

The aim of this study is to evaluate the therapeutic effects of up to 10 weeks of daily MFES-assisted gait training on spatiotemporal parameters, walking capacity, and motor recovery early after stroke. We hypothesise that stroke survivors will benefit from the therapeutic effect of MFES-assisted gait training by larger improvements on spatiotemporal parameters compared to conventional gait training. These data will inform the design of a sufficiently powered (multi-centre) randomised controlled trial. The strength of our study is that we investigate the effects of MFES during functional gait activities. Two out of three studies investigating MFES in the early phase after stroke applied MFES with the patient in a supine position.[24,25] Moreover, the stimulation periods in the three studies regarding this topic were only 3–4 weeks.[23-25] There is no evidence for the minimum intensity of MFES required to enhance recovery of walking capacity in stroke survivors. Different treatment doses of electrical stimulation have been studied in the past from 15 minutes up to all day long and from once to more sessions a day. The three studies investigating MFES in the early phase after stroke applied MFES for 30–45 minutes and found positive effects on several outcomes.[23-25] In our study, MFES will be applied each workday for minimally 15 minutes to maximally 30 minutes to aim for a feasible protocol in early stroke rehabilitation. Findings from this study will provide insight into the initial effects of MFES-assisted gait training on regaining gait symmetry and several other outcomes in early stroke rehabilitation. The collection of detailed data will generate new knowledge regarding early use of MFES to promote motor and gait recovery in the early phase after stroke. If this study confirms the feasibility and initial efficacy of MFES-assisted gait training, a larger study would be warranted to further determine the effectiveness of this intervention.

Trial status

At the time of manuscript submission, the enrolment of participants was ongoing at Merem Rehabilitation Centre De Trappenberg, Huizen, the Netherlands.

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Chapter 7

Feasibility and preliminary efficacy of gait training assisted by multichannel functional electrical stimulation in early stroke rehabilitation: a pilot randomized controlled trial

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Abstract

Background. Many stroke survivors suffer from leg muscle paresis, resulting in asymmetrical gait patterns, negatively affecting balance control and energy cost. Interventions targeting asymmetry early after stroke may enhance recovery of walking.

Objective. To determine the feasibility and preliminary efficacy of up to 10 weeks of gait training assisted by multichannel functional electrical stimulation (MFES gait training) applied to the peroneal nerve and knee flexor or extensor muscle on the recovery of gait symmetry and walking capacity in patients starting in the subacute phase after stroke.

Methods. Forty inpatient participants (≤31 days after stroke) were randomized to MFES gait training (experimental group) or conventional gait training (control group). Gait training was delivered in 30-minute sessions each workday. Feasibility was determined by adherence (≥75% sessions) and satisfaction with gait training (score ≥7 out of 10). Primary outcome for efficacy was step length symmetry. Secondary outcomes included other spatiotemporal gait parameters and walking capacity (Functional Gait Assessment and 10-Meter Walk Test). Linear mixed models estimated treatment effect postintervention and at 3-month follow-up.

Results. Thirty-seven participants completed the study protocol (19 experimental group participants). Feasibility was confirmed by good adherence (90% of the participants) and participant satisfaction (median score 8). Both groups improved on all outcomes over time. No significant group differences in recovery were found for any outcome.

Conclusions. MFES gait training is feasible early after stroke, but MFES efficacy for improving step length symmetry, other spatiotemporal gait parameters, or walking capacity could not be demonstrated.

Introduction

Many stroke survivors suffer from limitations in functional mobility and an increased fall risk.[1-4] Therefore, regaining independent walking is considered one of the primary goals in stroke rehabilitation.[4,5] However, only 60% to 80% of the stroke survivors achieve this ability.[3,5,6] After unilateral stroke, a limited walking capacity can be attributed to a variety of impairments on the paretic side, such as pes equinovarus, knee instability, and/or hip instability during the stance phase; and foot drop, limited knee flexion, and/or limited knee extension during the swing phase.[2,7,8] These impairments are largely the result of paretic leg muscle weakness and disrupted timing of muscle activations during gait.[3,4,7] The literature on gait restoration after unilateral stroke shows that, despite major improvements in gait independence, gait speed, and walking distance, the altered timing of muscle activity and the kinetic and kinematic gait abnormalities tend to persist,[4,9-11] which is why stroke survivors greatly rely on compensatory mechanisms by the trunk and the nonparetic leg, especially moderately to severely affected individuals.[2,4,9] As a result, their gait is often asymmetric and mechanically inefficient,[4,10,12-14] even though it can be considered “optimal” given the neuromechanical consequences of stroke.[12,15] Nevertheless, an asymmetric gait pattern forms a risk of overloading the trunk and the nonparetic side and is associated with limited gait adaptability, increased fall risk, fear of falling, and reduced physical activity.[1,2,16]

From this perspective, the ambition to restore gait symmetry is still an ultimate goal, which implies that the search for interventions to reduce gait asymmetry remains justified. Until now, several longitudinal studies reported persistent asymmetry during and after early rehabilitation,[9,10,13,14] while there are no therapeutic interventions with established effectiveness for improving gait symmetry in persons after unilateral stroke.[17,18] A possible reason is that controlled studies may not have focused specifically enough on improving gait symmetry by influencing kinetic and kinematic aspects of gait,[17,18] for instance, by combining training with a medical-technical intervention such as neuromuscular electrical stimulation.[13,19,20] Furthermore, many intervention studies measuring gait symmetry did not focus on the early time period (<12 weeks) poststroke,[17,18] during which neurological recovery of the paretic leg is most pronounced and the “window of opportunity” to restore gait symmetry is believed to be optimal.[3,9,20,21] Hence, there is a lack of studies focusing on gait training assisted by medical-technical applications in the early phase after stroke that aim to restore a symmetric gait pattern.

New techniques such as multichannel functional electrical stimulation (MFES) can facilitate gait training by supporting the activation of specific paretic leg muscles – adequately timed to the gait cycle – with the aim to promote a gait pattern that is as normal as possible.[2,4] When applied in the subacute phase after stroke, gait training assisted by MFES (MFES gait training) may push the central nervous system toward more effective reorganization[20] and support the reacquisition of an adequate gait pattern[22,23] by providing somatosensory input,[23-25] maintain physical and physiological

body characteristics,[23-25] and prevent inappropriate compensations and secondary complications.[23,25]

Until now, there is little evidence for the feasibility and efficacy of MFES as an adjunct to conventional gait rehabilitation early after unilateral stroke to restore gait symmetry. Four small randomized controlled trials (RCTs) suggested that MFES, adequately timed to the gait cycle, early after stroke may improve motor function, balance control, gait speed and capacity, and functional activities of daily living.[22,26-28] However, these studies had a high risk of bias by incomplete reporting of subject selection and results,[22,26] unblinded outcome assessments,[22,27] loss to follow-up,[28] and imprecision of effect estimates due to small sample sizes and poor statistical analyses.[22,26-28] Moreover, three out of four studies were not dose-matched and investigated MFES in a supine position independent of gait rehabilitation.[26-28] Only 1 small RCT (n=13) investigated the efficacy of gait training assisted by MFES, but did not report on gait symmetry.[22] Therefore, it remains unknown whether conventional gait training assisted by MFES is feasible and effective for the restoration of gait symmetry early after unilateral stroke.

The present pilot RCT aimed to fill this knowledge gap by determining the feasibility and preliminary efficacy of up to 10 weeks of gait training assisted by surface-based MFES applied to both the peroneal nerve and a knee flexor (biceps femoris brevis) or extensor (vastus medialis) muscle. MFES gait training was compared with dose-matched conventional gait training regarding the restoration of step length symmetry (primary outcome) and other spatiotemporal parameters and walking capacity (secondary outcomes) in an inpatient rehabilitation population. Step length symmetry was considered a good measure of gait symmetry, because adequate bilateral step length is determined by kinematic characteristics of the swing phase (eg, sufficient hip flexion, knee extension, and ankle dorsiflexion) and indirectly by kinetic characteristics of the stance phase (eg, sufficient stance stability, ankle power, and propulsive impulse).[7,8,29] Moreover, this parameter has shown to respond to the beneficial effects of implanted peroneal nerve stimulation in chronic stroke survivors, particularly in those with relatively pronounced step length asymmetry at baseline.[30,31]

Methods

We performed a stratified single-center, assessor-blinded, pilot RCT and randomized 40 participants to either the experimental group, receiving MFES gait training, or the control group, receiving gait training as usual. Computer-generated 4-block randomization and allocation was effectuated by an independent researcher allowing concealment for the next allocation. Randomization was stratified by functional walking capacity at enrolment, that is, “dependent gait” (Functional Ambulation Categories 1 and 2) versus “independent gait” (Functional Ambulation Categories 3 to 5). The intervention period lasted 10 weeks

or until discharge from inpatient rehabilitation, whichever came first. Until data analysis was completed, the randomization was concealed to the primary researcher (MVB) and the outcome assessors and the participants were instructed not to reveal their group allocation. To ensure integrity of blinding, data were analyzed by an independent statistician. The RCT was registered in the Netherlands Trial Register (NTR4762) and the study protocol of this RCT was described in detail previously.[32]

The study protocol was approved by the Medical Ethics Committee of the Academic Medical Center of the Amsterdam University Medical Centers (protocol number NL50002.018.14) and conformed to the standards set by the Declaration of Helsinki. Participants provided written consent prior to enrolment.[32]

Trial setting and participants

Participants were recruited from one Dutch rehabilitation center (Merem Medical Rehabilitation, Huizen). All stroke survivors admitted for inpatient rehabilitation from November 2014 to September 2017 were screened for eligibility by their physiatrist.[32] The inclusion criteria were: clinical diagnosis of unilateral stroke; being within 31 days since stroke onset; age 18 to 80 years; indication for gait training (indicated in case of restrictions in walking activities and impairments in gait and/or balance); able to walk with or without aids and physical assistance from one physical therapist; and range of motion on passive ankle dorsiflexion ≥0° with full knee extension. Exclusion criteria were as follows: subarachnoid hemorrhage or cerebellar or brainstem stroke; severe spasticity of knee or ankle flexors or extensors (ie, Modified Ashworth Scale ≥3); medical comorbidities that might significantly interfere with gait (including a previous stroke with persisting gait deficits); severe cognitive problems or aphasia that might interfere with the ability to comprehend test instructions (based on clinical judgment); medical conditions that might lead to inability to comply with the study protocol; demand-type cardiac pacemaker, defibrillator or electrical implant; metallic implant at the paretic leg; or cancerous lesion at the paretic leg.

Interventions

Both groups received individualized conventional gait training for 30 minutes on weekdays (dose-matched). Individualized conventional gait training included improving walking distance and endurance, walking on uneven and smooth surfaces, walking with dual tasks, improving gait speed and adaptability, improving standing and walking balance, ramp ascent and descent walking, obstacle avoidance, functional gait activities, all with attention to gait quality. Most gait training sessions were overground, but treadmill walking was performed as well. Walking aids, orthoses, orthopedic shoes, and medication could be used. Additionally, participants received gait training in groups, fitness training, sports, and hydrotherapy depending on their personal needs and interests. In the experimental group, individualized conventional gait training was assisted by MFES (MFES gait training).

Physical therapists, specifically trained in the protocol and use of MFES, carried out the gait training.

The MFES device used in this study (NESS L300 Plus, Bioness) delivers electrical pulses to muscles in the paretic leg to promote ankle dorsiflexion in combination with knee flexion or extension during gait. The electrodes of the lower leg cuff are positioned over the common peroneal nerve and the tibialis anterior muscle to elicit active ankle dorsiflexion. The lower leg stimulation starts at "heel off" and gradually terminates after "heel contact", as it can be extended beyond heel contact to control the first rocker. The electrodes of the thigh cuff are positioned over the vastus medialis muscle (ventral positioning) to promote knee extension or over the biceps femoris brevis muscle (dorsal positioning) to promote knee flexion. With this configuration, either paretic muscles can be stimulated or excessive stiffness of spastic muscles can be counterbalanced.[23-25,32,33] Authorized clinicians observed the gait pattern, performed additional tests (eg, muscle strength and spasticity), and determined which gait aspect (ie, stance stability, step length, foot clearance, foot prepositioning, or energy conservation) was inadequate and had priority to be improved. The vastus medialis muscle was stimulated to influence excessive knee flexion during the stance phase, or reduced knee extension during the stance or swing phase; or the biceps femoris brevis muscle was stimulated to influence knee hyperextension during the stance phase, or reduced knee flexion during the swing phase.[32] The effect of the MFES settings on the impaired gait aspect were evaluated and fine-tuned by gait observation to achieve the best possible gait pattern. The thigh stimulation could start and end once or twice at any segment in the gait cycle. Further information about the MFES settings has been reported elsewhere.[32] The authorized clinicians (physical therapists and orthotists) were specifically trained to fit the MFES device and set the stimulation parameters. They fitted the device at baseline and fine-tuned the settings of the device every 2.5 weeks.

Outcomes

Adherence was assessed by recording the number of sessions per week the participant attended during the training period, as monitored by the therapists. Participant satisfaction was assessed postintervention. Satisfaction with the experimental or conventional gait training was assessed on a 10-point numeric rating scale from 0 ("most unsatisfied") to 10 ("most satisfied"). Moreover, satisfaction of the participants in the experimental group with the MFES device was evaluated by a questionnaire with 5-point Likert-type scales (1 = very unsatisfied, 2 = unsatisfied, 3 = neutral, 4 = satisfied, 5 = very satisfied) addressing comfort of wearing, quality of the gait pattern, walking distance, gait speed, effort of walking, stability during walking, and walking stairs.

Spatiotemporal gait parameters were assessed at baseline, 6 six weeks intervention, postintervention (maximally after 10 weeks), and at 3-month follow-up after cessation of the intervention. Additional secondary outcomes were assessed every 2 weeks during the intervention period as well as at 3-month follow-up.

The primary outcome of the efficacy study was step length symmetry. Step length during comfortable gait speed was measured with a customized spatiotemporal gait analysis system (SGAS).[34] Participants walked along a 10-m walkway until 5 valid left and right foot steps were collected in which each foot landed within the 130-cm-wide video field-of-view. The primary condition was walking without shoes and orthosis with as minimal as possible use of walking aids or physical assistance. The secondary condition was shod walking with as minimal as possible support.

Step length was calculated as the distance between the position of initial contact of one foot and the position of initial contact of the opposite foot in the sagittal plane (determined by the position of the heels or, in case of mid- or fore-foot landing, the toes). Step length symmetry was expressed as an index of asymmetry: the absolute difference between the step length of the paretic and nonparetic leg divided by the mean step length of both legs, multiplied by 100%.[35] An index with an inter-limb difference score as numerator was used, because a simple symmetry ratio might easily be inflated and show a skewed distribution.[15,35,36] In addition, the absolute difference score was used, because step length asymmetry after stroke may go in either direction and gait training was aimed to restore each type of asymmetry toward symmetric gait. One-hundred percent was imputed for indexes exceeding this percentage (in cases where the swinging foot landed next to the opposite standing foot, giving a negative or small positive step length of one leg in contrast to a relatively large step length of the opposite leg). A value of 0% indicates perfect symmetry, while 100% indicates maximal asymmetry. Normative data are available for stroke survivors as well as for healthy adults.[35,36] We applied a cut-off point for the step length asymmetry index of <7.6% as normal.[36] To our knowledge, the minimal clinically important difference and minimal detectable change for step length asymmetry have not been reported.

The secondary outcomes of the efficacy study were additional spatiotemporal gait parameters (step time asymmetry index, single-leg stance time asymmetry index, stride length, and stride time) for the barefoot and shod conditions,[34-36] walking capacity measures (walking balance measured with the Functional Gait Assessment[37,38] and comfortable gait speed calculated from the 10-Meter Walk Test[37]), and balance control measured with the Berg Balance Scale.[39] Furthermore, fear of falling was evaluated by the Falls Efficacy Scale I (score range 16–64) and assessed only at 3-month follow-up.[40]

Adverse events

All adverse events were documented, regardless of their relationship to the MFES gait training, by the primary researcher or staff at each visit.[32]

Statistical analysis

Sample size was based on the feasibility of recruitment in one center (yearly admission rate of 80 stroke survivors) within 2 years and set at 40 participants (20 in each group).[32]

In the absence of data on variance in step length symmetry, a sample size calculation could not be performed. However, we expected that a sample size of 40 participants would be large enough to inform the inclusion needed in a larger trial.[41]

In order to assess the feasibility of the intervention, we evaluated adherence (based on the proportion of participants in the experimental group who attended ≥75% of the protocolled gait training sessions) and satisfaction with gait training (based on a score ≥7 on the numeric rating scale for participant satisfaction).

Primary efficacy analysis was performed on an intention-to-treat basis, including all participants who were randomized. In addition, a per-protocol analysis was performed for the primary outcome and was based on the participants with an intervention period of at least 5 weeks and who completed all assessments. Furthermore, subgroup analysis was performed for the primary outcome and was based on the participants with step length asymmetry at baseline (step length asymmetry index ≥7.6%).

Linear mixed models were used to assess the effect of treatment on the primary and secondary outcomes.[42,43] All longitudinal analyses modeled the change from baseline as a function of time since randomization, adjusted for treatment, baseline value, and the stratification factor (Functional Ambulation Categories). All linear mixed models incorporated a random intercept per subject to account for the within-subject clustering. Time since randomization was modeled nonlinearly using natural splines with two degrees of freedom.[43] Treatment effect was assessed by adding an interaction term between time since randomization and treatment. The likelihood ratio test was used to determine the significance of the interaction.[43] The assumption on normality of the residuals was visually checked.

Considering the nonnormally distributed data of the participant satisfaction outcomes and Falls Efficacy Scale I, group comparisons postintervention and at follow-up were performed using Mann-Whitney *U* tests. In all analyses, statistical uncertainty was expressed by means of 95% confidence intervals. Significance was set at $p<.05$. All statistical analyses were performed in R version 3.5.1.[44] Linear mixed models were fitted using the *lmer* function in the R package lme4 (version 1.1–19).[45] Plots were generally constructed by using the *ggplot* function in the package ggplot2 (version 3.1.0).[46]

Results

Of 188 persons consecutively admitted to inpatient stroke rehabilitation, 40 (21%) met the study criteria and agreed to participate. Figure 7.1 details the participant flow through the trial and reasons for dropout. Before baseline measurement, 2 randomized participants dropped out. A third participant dropped out during baseline assessment because of incorrect inclusion (unable to walk with aids and physical assistance from 1 physical therapist and severe cognitive problems). This participant was therefore excluded from analysis.

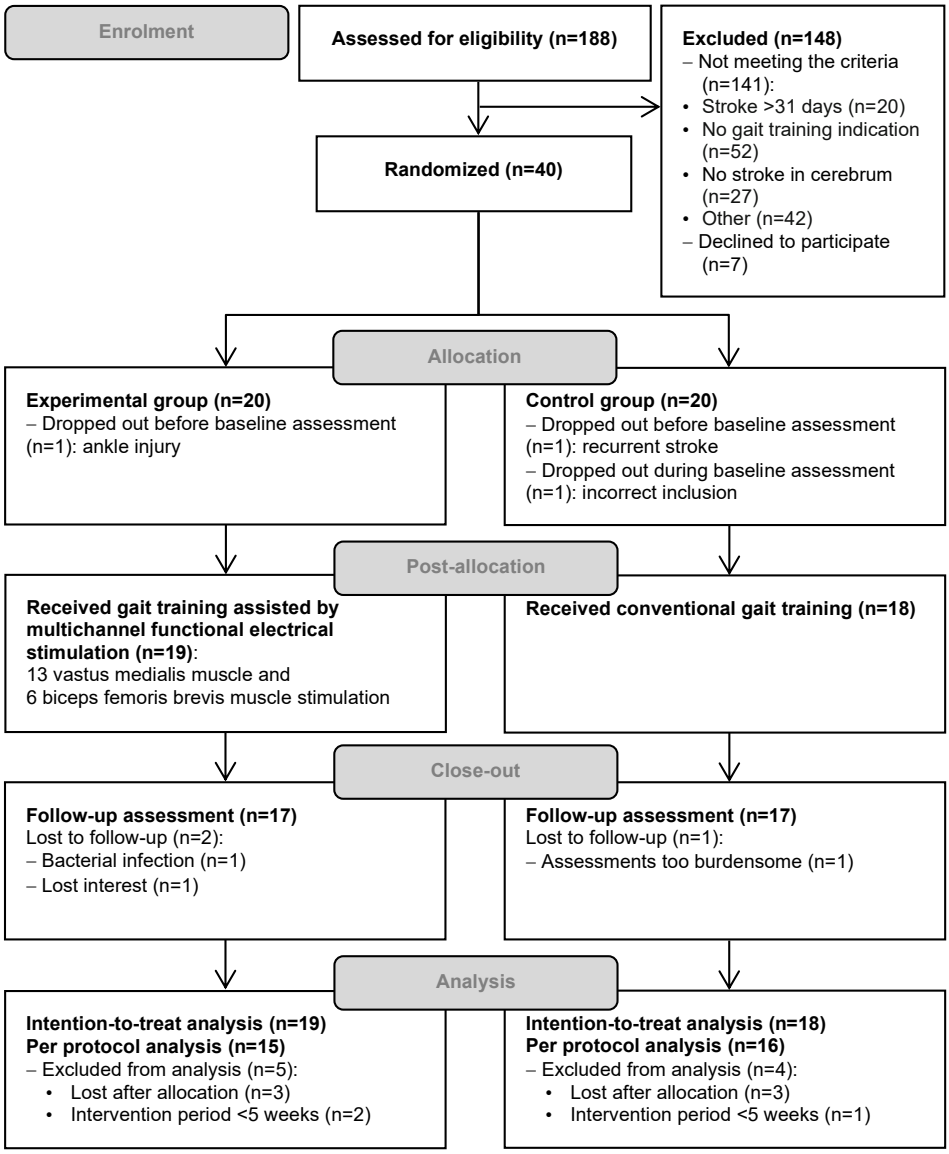


Figure 7.1. The flow of participants through the study.

Of the 37 participants, 19 were randomized to the experimental intervention and 18 to conventional gait training. Sociodemographic and stroke characteristics are shown in Table 7.1. In the experimental group, 13 participants received stimulation of the vastus medialis muscle and 6 of the biceps femoris brevis muscle. Supplement 7.1 provides information about the individual MFES device settings and training duration. For the per-protocol analysis, 31 participants (15 in the experimental group and 16 in the control group) were included (Figure 7.1). At baseline, 10 participants in the experimental group

and 11 participants in the control group used walking aids (quad cane, cane, or rolling walker). Four participants in each group required an ankle-foot orthosis. Over time, the use of walking aids and orthoses changed in both groups, but this did not differ between groups (detailed information in Supplement 7.2). Low-dose benzodiazepines were used by 1 participant in the experimental group and by 2 participants in the control group. Low-dose antispasmodics were used by one participant in the experimental group. No antipsychotics were used.

Feasibility

The percentage of completed gait training sessions was 79% (mean total number of sessions 26 ± 9, range 7–39) for the experimental group and 79% (mean total number of sessions 27 ± 10, range 11–40) for the control group. Of the participants in the experimental group, 90% attended ≥75% of the MFES gait training sessions. The duration of gait training did not differ between the experimental group (mean 7.0 ± 2.0 weeks) and control group (mean 7.9 ± 2.5 weeks, p=.25). Per session, participants in the experimental group received approximately 20 minutes of MFES gait training due to donning and doffing of the device. Participants in the control group received approximately 25 minutes of gait training per session.

Satisfaction of the experimental group with MFES gait training ranged from 7 to 10 (median score 8 [P25; P75 8; 10]) and did not differ from the scores in the control group ranging from 7 to 10 (median score 8 [P25; P75 8; 9], p=.58). The participants were generally satisfied with the MFES device (comfort of wearing, walking distance, gait speed, and walking stairs median score 4 [P25; P75 3; 5]; quality of the gait pattern median score 4 [P25; P75 4; 5]; and effort of walking and stability during walking median score 4 [P25; P75 3; 4]).

Step length symmetry

Step length symmetry improved in both groups over time (Table 7.2). Step length symmetry was not normally distributed, therefore log-transformation was applied for statistical analyses. No group difference in step length symmetry was found on an intention-to-treat basis (log-transformed % estimated group difference of -0.07 with 95% confidence interval -0.50 to 0.36, p=.99; Table 7.2 and Figure 7.2 panel A) nor on a per-protocol basis (log-transformed % estimated group difference -0.17 with 95% confidence interval -0.64 to 0.31, p=.87; Supplement 7.3 and 7.4 panel A). Natural splines were included in the models. Individual trends are shown in Figure 7.3. Similarly, subgroup analysis based on participants with step length asymmetry at baseline (16 participants in the experimental versus 14 participants in the control group) revealed no group differences (log-transformed % estimated group difference -0.03 with 95% confidence interval -0.53 to 0.48, p=.95; Supplement 7.3 and 7.4 panel B).

Table 7.1. Baseline characteristics and scores

Characteristic	Total group (n=37)		Subgroup with ≥7.6% step length asymmetry (n=30)	
	Experimental group (n=19)	Control group (n=18)	Experimental group (n=16)	Control group (n=14)
Gender, male:female[a]	15 (79%) : 4 (21%)	14 (78%) : 4 (22%)	12 (75%) : 4 (25%)	11 (79%) : 3 (21%)
Age, years[b]	57.0 ± 8.7	58.7 ± 10.2	56.6 ± 8.9	57.8 ± 11.4
Body Mass Index, kg/m^2[c]	25.4 (23.2; 28.8) (n=17)	25.6 (24.0; 27.2)	26.3 (24.6; 29.0) (n=14)	25.8 (24.0; 28.6)
Stroke etiology, ischemic:hemorrhagic[a]	16 (84%) : 3 (16%)	15 (83%) : 3 (17%)	13 (81%) : 3 (19%)	12 (86%) : 2 (14%)
Hemisphere lesion, left:right[a]	5 (26%) : 14 (74%)	9 (50%) : 9 (50%)	4 (25%) : 12 (75%)	8 (57%) : 6 (43%)
Tactile neglect present[a]	3 (16%)	5 (28%)	2 (13%)	3 (21%)
Visual neglect present[a]	5 (26%)	5 (28%)	4 (25%)	3 (21%)
Time since stroke, days[c]	16 (14; 24)	20 (17; 24)	17 (14; 27)	20 (16; 24)
Functional walking capacity, FAC score[c]	2 (2; 3)	2 (2; 3)	2 (2; 3)	2 (2; 3)
Balance control, BBS score[c]	36 (31; 48)	40 (21; 49)	35 (30; 47)	33 (17; 47)
Muscle strength, MI lower extremity score[c]	66 (48; 79)	64 (49; 75)	60 (41; 77)	62 (44; 74)
* Ankle[c]	14 (14; 25)	19 (10; 25)	14 (13; 27)	14 (9; 25)
* Knee[c]	25 (25; 29)	25 (21; 25)	25 (22; 25)	25 (21; 25)
* Hip[c]	19 (14; 25)	19 (14; 25)	17 (14; 25)	20 (10; 25)
Motor selectivity, BFMA lower extremity score[c]	24 (16; 27) (n=18)	24 (18; 29)	23 (12; 26) (n=15)	20 (16; 25)
Tactile sensation, EmNSA lower extremity, n (normal/impaired/absent)	10/6/3	9/4/4 (n=17)	7/6/3	7/3/4
Proprioceptive sensation, EmNSA lower extremity, n (normal/impaired/absent)	11/8/0	7/9/0 (n=16)	8/8/0	5/7/0 (n=12)
Passive range of motion of the gastrocnemius muscle paretic side (degrees dorsiflexion)[c,d]	5.0 (0.0; 7.5)	2.5 (0.0; 5.0)	5.0 (-1.3; 6.3)	2.5 (0.0; 5.0)
Muscle tone of the gastrocnemius muscle paretic side, MAS, n (normal/increased)	12/6 (n=18)	14/4	10/5 (n=15)	11/3

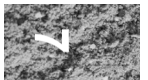
Abbreviations: FAC, Functional Ambulation Categories (range 0–5); BBS, Berg Balance Scale (range 0–56); MI, Motricity Index (range 0–100); BFMA, Brunnström Fugl-Meyer Assessment (range 0–34); EmNSA, Erasmus Medical Center modified Nottingham Sensory Assessment; MAS, Modified Ashworth Scale I.

[a] Data are expressed as number and percentage and compared with the Fisher exact test (2-tailed).

[b] Data are expressed as mean ± standard deviation and compared with the independent-samples *t* test.

[c] Data are expressed as median and 25th and 75th percentiles and compared with Mann-Whitney *U* tests.

[d] Dorsiflexion measured with extended knee.



A comparable result as for barefoot walking was found for step length symmetry in the shod condition (log-transformed % estimated group difference -0.03 with 95% confidence interval -0.56 to 0.52, *p*=.46; Supplement 7.3 and 7.4 panel C).

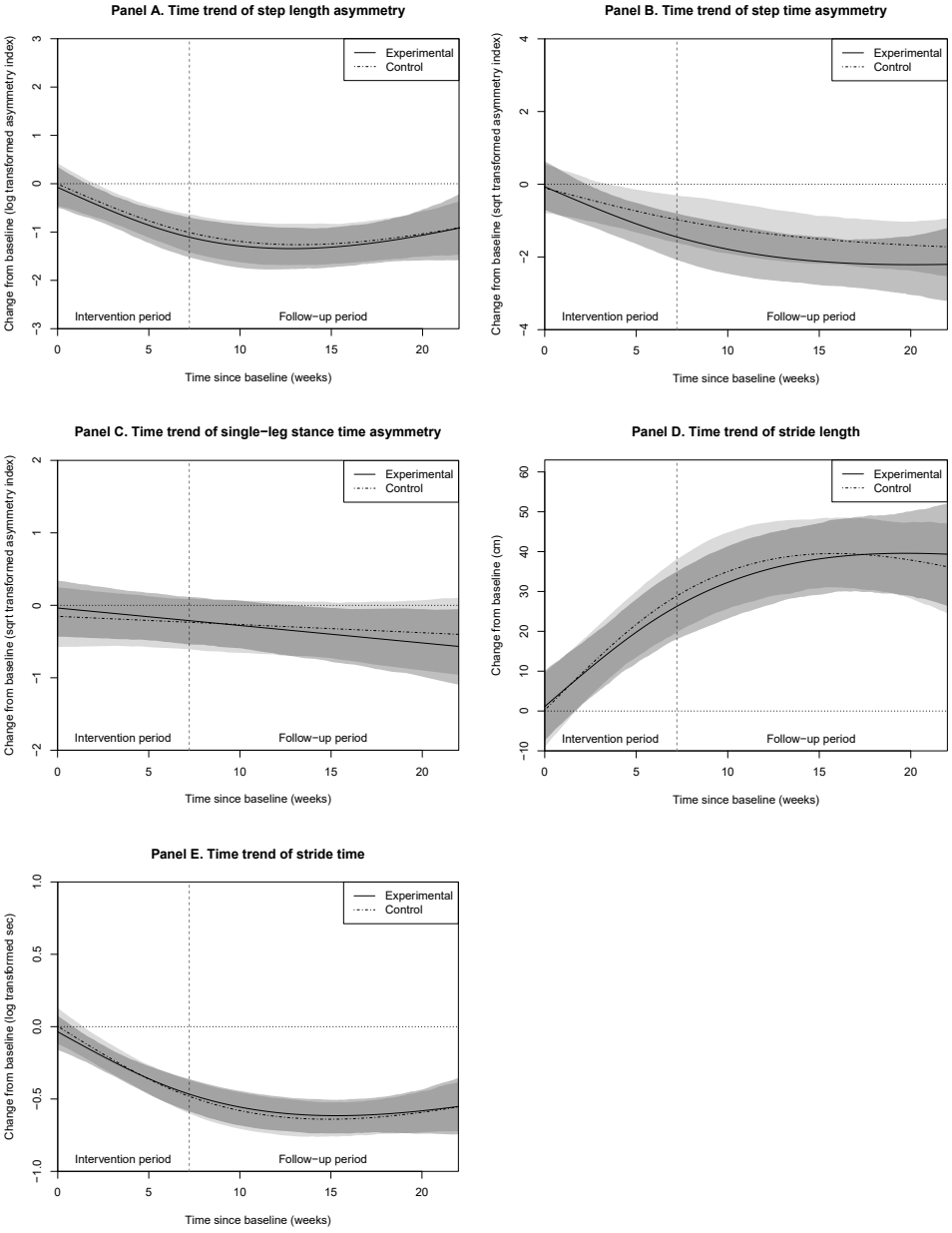


Figure 7.2. Time trends of asymmetry indexes and strides for both groups: the shaded areas indicate the 95% confidence intervals of the group means (light gray is control group, middle gray is experimental group, and dark gray is overlap between both groups). The vertical gray dashed line marks the end of the intervention period (overall mean).

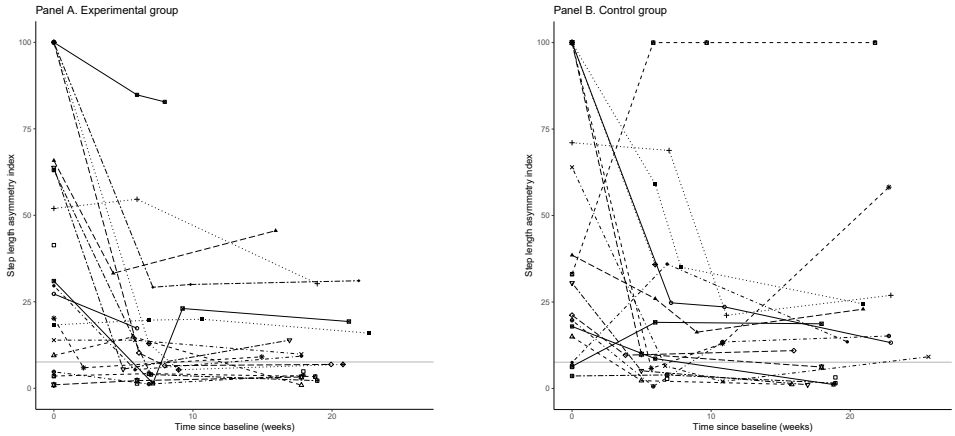


Figure 7.3. Individual time trends of step length asymmetry (indicated with unique symbols per individual) for both groups: the horizontal gray line represents the normative cutoff point. The symbols indicate the assessments (baseline, if applicable after 6 weeks intervention, postintervention (maximally after 10 weeks), and at 3-month follow-up).

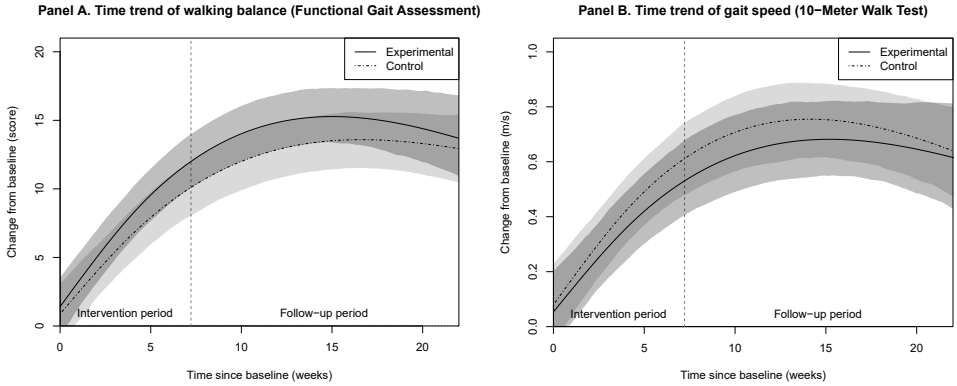


Figure 7.4. Time trends of clinical outcomes for both groups: the shaded areas indicate the 95% confidence intervals of the group means (light gray is control group, middle gray is experimental group, and dark gray is overlap between both groups). The vertical gray dashed line marks the end of the intervention period (overall mean).

Secondary outcomes

Both groups showed improvements on all outcomes over time, except for single-leg stance time symmetry in the control group (Figure 7.2). No significant group differences were found for any of the secondary outcomes (Table 7.2 and Figure 7.4). The outcomes of the shod condition and Berg Balance Scale are presented in Supplement 7.3 and 7.4. Fear of falling, measured with the Falls Efficacy Scale I, at 3-month follow-up did not differ significantly (p=.72) between the experimental (median score 20 [P25; P75 19; 22], n=17) and control group (median score 20 [P25; P75 17; 26], n=15).

Adverse events

One adverse event was reported concerning MFES gait training. A participant developed a small wound localized in the popliteal fossa due to movement of the thigh cuff, which did not require medical treatment. Tighter attachment of the cuff solved the skin irritation. One adverse event was reported concerning the assessments. A participant in the control group perceived the assessments as too burdensome and discontinued study participation (Figure 7.1).

Discussion

Our study showed that MFES gait training, initiated in the first month after stroke and continued for up to 10 weeks during inpatient rehabilitation, was feasible and well appreciated. However, our results suggest that MFES gait training was not superior to conventional gait training for improving gait symmetry, other spatiotemporal gait parameters, or walking capacity. Both groups demonstrated similar improvements following the intervention period. The plateaus in the recovery trends seen at follow-up (Figures 7.2 and 7.4) were in accordance with previously reported recovery patterns for walking and activities of daily living in stroke survivors receiving rehabilitation.[9,14,47-49]

Table 7.2. Effects of gait training assisted by multichannel functional electrical stimulation in the experimental group compared with the control group (intention-to-treat analysis)

		Raw values[a]			Effect			
Outcome measures	G	Baseline	Post-intervention	3-month follow-up	Trans-formed data	Estimated group difference	95% CI (profile likelihood)	*p*
Step length asymmetry index – barefoot	E	31.0 (16.1; 64.8)	6.5 (4.8; 21.5)	9.1 (3.8; 15.9) (n=17)	log	-0.07	-0.50 to 0.36	.99
	C	31.8 (15.7; 92.8)	13.2 (6.0; 23.0)	13.2 (3.2; 22.9) (n=17)				
Step time asymmetry index – barefoot	E	40.9 (14.0; 60.5)	17.2 (10.1; 29.5)	15.0 (4.1; 26.6) (n=17)	sqrt	-0.33	-1.03 to 0.38	.56
	C	28.4 (23.3; 50.3)	21.4 (4.4; 47.4)	15.9 (3.8; 20.1) (n=17)				
Single-leg stance time asymmetry index – barefoot	E	10.6 (7.0; 16.0)	11.6 (6.2; 14.4)	9.9 (3.2; 15.3) (n=17)	sqrt	0.01	-0.45 to 0.47	.53
	C	14.4 (4.3; 18.8) (n=17)	11.2 (3.7; 17.2)	7.3 (2.8; 18.1) (n=17)				
Stride length – barefoot (cm)	E	52.7 (46.0; 72.9)	85.5 (76.5; 101.2) (n=18)	95.2 (83.6; 109.4) (n=13)	no	-0.29	-10.84 to 10.18	.78
	C	43.0 (38.4; 75.5) (n=17)	76.8 (48.0; 105.5) (n=16)	101.1 (66.5; 116.7) (n=15)				
Stride time – barefoot (s)	E	1.77 (1.54; 2.97)	1.26 (1.23; 1.63) (n=18)	1.29 (1.10; 1.40) (n=13)	log	-0.01	-0.12 to 0.11	.88
	C	1.78 (1.37; 4.61) (n=17)	1.30 (1.12; 2.16) (n=16)	1.23 (1.11; 1.73) (n=15)				
Functional Gait Assessment (score range 0–30)	E	7.0 (3.0; 9.0)	19.0 (13.0; 25.0)	26.0 (18.0; 26.0) (n=17)	no	1.27	-1.31 to 3.84	.58
	C	5.0 (1.3; 10.0)	18.5 (9.3; 22.8)	24.0 (13.0; 26.0) (n=17)				
Comfortable 10-Meter Walk Test (m/s)	E	0.42 (0.30; 0.62) (n=15)	1.00 (0.68; 1.18)	1.23 (0.75; 1.38) (n=16)	no	-0.05	-0.22 to 0.11	.83
	C	0.28 (0.17; 0.65) (n=15)	0.95 (0.44; 1.24)	1.11 (0.60; 1.36) (n=17)				

Abbreviations: G, Group; E, Experimental group (n=19); C, Control group (n=18); log, log-transformed data; sqrt, square root transformed data.
[a] Median score and 25th and 75th percentiles (data were non-normally distributed).

Our hypothesis was that MFES gait training started early after stroke – within the presumed critical time window for neuroplasticity – would improve step length symmetry and prevent inadequate compensatory motor strategies, thereby facilitating a more normal gait pattern. However, MFES gait training appeared to be no more effective than conventional gait training. In both groups gait symmetry improved, except for single-leg stance time symmetry in the control group (Figures 7.2 and 7.4 and Table 7.2). On an individual level, the time trends were diverse, while 19% of the participants already had a symmetric step length at baseline (Figure 7.3). Because a ceiling effect in these participants could have biased the results, we performed a post-hoc subgroup analysis including only the 30 participants with step length asymmetry at baseline. This analysis showed similar results as the primary analysis of the entire study sample.

In the literature, there is conflicting evidence about the persistence of gait asymmetry after stroke. Previous small, short-term studies in diverse stroke populations have shown increases in gait symmetry over time.[17,19] Other studies, however, reported no improvement in step length or swing time symmetry during inpatient rehabilitation after stroke up to 6 months follow-up.[9,10,13,14] Given the potential long-term consequences of persisting gait asymmetry (ie, increased risk of falls and injuries, reduced gait efficiency, poor aesthetics, risk of muscle shortening, joint deformation, and pain complaints), restoration of gait symmetry remains an important clinical issue. However, based on the available evidence, it is still questionable whether restitution of motor function after stroke can be influenced by training interventions beyond the influence of spontaneous neurological recovery. Although step length symmetry must be regarded as a surrogate outcome for restitution of motor function after unilateral stroke, it is most likely strongly influenced by the restoration of motor control of the paretic leg in terms of its kinematic and kinetic characteristics.[7,8,29] Until now, neither animal nor human studies have been able to show that leg motor impairments after stroke can be restored by specific training interventions to improve the quality of motor performance.[48,50,51] This is supported by the growing body of evidence suggesting that the degree of leg motor recovery after stroke is highly predictable in terms of synergism and muscle coordination, showing an almost invariant proportional relationship between leg motor impairment early after stroke and after 6 months.[3,9,47,48,51] Hence, currently there is insufficient evidence to recommend the clinical use of MFES in early stroke rehabilitation.[25,52-54] This is in line with the outcome of our study and the lack of evidence from earlier studies investigating the efficacy of daily 30 to 45 minutes of isolated MFES applied to the knee and ankle flexors and extensors early after stroke.[22,26-28]

The current study has several limitations, some of which are inherent in our aim to investigate feasibility and preliminary efficacy. First, this pilot trial may have been underpowered for efficacy assessment. Nevertheless, we do not suspect a false negative outcome based on the small, non-significant estimated treatment effects (Table 7.2) and the extensive overlap between the recovery trends in the models of the experimental and control group (Figures 7.2 and 7.4). Second, the inclusion criteria for selecting participants

may not have been optimal, as 19% of the participants already had a symmetrical step length at baseline. Although subgroup analysis including only the participants with step length asymmetry at baseline showed similar results as the primary analysis, we were unable to take into account initial leg motor function given the small sample size. The differential response to training (Figure 7.3) suggests that future MFES studies with the aim to restore gait symmetry should focus on individuals with initial gait asymmetry and with a fair potential for restoration of leg motor function.[12,15,18,19,48,51] Third, using quantitative gait analysis instead of visual analysis to determine the position and parameter settings of MFES would have increased standardization and precision, but we preferred to use a standardized clinical approach from a pragmatic, clinical perspective. Fourth, as argued above, step length symmetry must be considered a surrogate outcome measure for restoration of motor control of the paretic leg, which is why future studies should also incorporate kinematic and kinetic gait characteristics and muscle activation patterns. Fifth, the spatiotemporal gait data were characterized by a high stride-to-stride variability, which might have been due to a short warming-up period and a small number of repetitions.[55] The number of 5 steps per leg was chosen to minimize the burden on participants. The impact of this choice on our results remains unknown. For future studies, we recommend to extend the warming-up period and increase the number of strides to assess gait symmetry. Sixth, the intensity levels (amplitudes) of MFES turned out to differ per training session, but this was not accurately logged by the therapists. In future studies, MFES settings should be logged during the entire period of gait training to better control for treatment intensity. Seventh, the applied dose (approximately 20 minutes MFES gait training per working day) may have been insufficient. Moreover, the intervention period and therefore the total dose differed substantially between participants (Supplement 7.1). Yet, we provided the largest feasible dose that could be administered during regular gait training at our rehabilitation center given the participants' length-of-stay. Intensifying MFES gait training may not be feasible unless the training is combined with daily "orthotic" application of MFES during the period of (in- and outpatient) gait rehabilitation. Indeed, there is preliminary evidence for the notion that such "orthotic" use of functional electrical stimulation is able to promote gait symmetry after unilateral stroke.[30,31,56]

Conclusions

This pilot RCT showed that MFES gait training initiated in the subacute phase after unilateral stroke is feasible. Nevertheless, efficacy for improving step length symmetry, other spatiotemporal gait parameters, or walking capacity in a fairly unselected group of typical rehabilitation inpatients seems similar to conventional gait training. Our results, however, do not preclude beneficial effects of MFES gait training in a more targeted population with a better potential for the restoration of gait symmetry.

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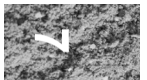
Supplement 7.1.

Information about MFES device and gait training.

Supplement 7.1. Overview MFES device settings at baseline and training duration

Person	Intended purpose	MFES device settings[a]						Training duration	
		Thigh stimulation parameters				Lower leg stimulation parameters		Full weeks inpatient rehabilitation[c]	Total of FEST sessions
		Stimulated muscle	Phase duration (µsec)	Pulse rate (Hz)	Stimulation period (%)[b]	Phase duration (µsec)	Pulse rate (Hz)		
1	Foot clearance during swing phase and stability during stance phase	Bf	200	35	St 60-100 / Sw 0-60	300	35	5	22
2	Foot clearance during swing phase	Bf	300	35	10-35	300	35	9	36
3	Foot clearance and increase step length	Vm	300	40	St 0-5 / Sw 70-100	300	35	1	7
4	Foot clearance during swing phase and stability during stance phase	Vm	300	30	St 0-80	300	25	8	30
5	Stability during stance phase	Vm	300	40	St 10-80	300	35	7	30
6	Foot clearance during swing phase and stability during stance phase	Bf	300	40	St 0-40 / Sw 85-100	300	30	6	21
7	Foot clearance during swing phase and stability during stance phase	Vm	300	35	St 10-100 / Sw 0-15	300	30	6	33
8	Foot clearance during swing phase	Bf	300	40	Sw 10-80	300	35	7	28
9	Foot clearance during swing phase and stability during stance phase	Vm	300	40	St 0-40 / Sw 60-100	300	25	6	26
10	Foot clearance and prepositioning during swing phase and increase step length	Vm	200	40	St 0-80	200	40	10	34
11	Foot clearance during swing phase	Bf	300	40	Sw 30-60	300	30	5	17
12	Prepositioning foot in terminal swing	Vm	300	40	Sw 80 - St 15	300	35	3	12
13	Foot clearance and prepositioning during swing phase and stability during stance phase	Vm	300	40	St 10-80	300	30	9	39
14	Prepositioning foot in terminal swing and stability during stance phase	Vm	200	40	St 10-80	200	30	6	28
15	Foot clearance during swing phase	Bf	200	40	Sw 30-80	300	40	5	23
16	Prepositioning foot in terminal swing and increase step length	Vm	300	40	St 15-80	200	30	5	16
17	Foot clearance during swing phase and stability during stance phase	Vm	200	40	St 0-35	300	30	5	27

Supplement 7.1 continues on the next page.



Supplement 7.1. *Continued*

Person	Intended purpose	MFES device settings[a]						Training duration	
		Thigh stimulation parameters				Lower leg stimulation parameters		Full weeks inpatient rehabilitation[c]	Total of FEST sessions
		Stimulated muscle	Phase duration (µsec)	Pulse rate (Hz)	Stimulation period (%)[b]	Phase duration (µsec)	Pulse rate (Hz)		
18	Foot clearance during swing phase and stability during stance phase	Vm	200	40	St 15-90	300	35	5	27
19	Foot clearance during swing phase and stability during stance phase	Vm	300	35	St 20-90	300	35	9	39

MFES, multi-channel functional electrical stimulation; FEST, gait training assisted by MFES; Vm, vastus medialis muscle; Bf, biceps femoris brevis muscle.
[a] The maximum duration of stimulation for thigh and lower leg stimulation was 4 sec and the waveform was symmetric.
The intensity level (milliampere) varied and was adjusted to each participant's maximum tolerable intensity and the optimal visible effect on leg movement.
[b] Stimulation period 0-100% swing phase (Sw) and/or 0-100% stance phase (St).
[c] Only full weeks of inpatient rehabilitation are incorporated (no start or discharge during the week).

Supplement 7.2.

Information about walking aids and orthoses use during assessments.

Supplement 7.2. Overview of number of participants using walking aids and orthoses during laboratory and clinical assessments

		Time point					
		Baseline		Post-intervention		3-month follow-up	
		Experimental group (n=19)	Control group (n=18)	Experimental group (n=19)	Control group (n=18)	Experimental group (n=17)	Control group (n=17)
Spatiotemporal gait assessment							
Physical assistance required		2	3	0	0	0	0
Walking aids	None	13	12	18	15	17	15
	Cane	0	0	0	0	0	bf: 2 / s: 1
	Quad cane	5	6	1	3	0	bf: 0 / s: 1
	Rolling walker	1	0	0	0	0	0
Orthoses	None	18	14	16	14	15	14
	Dorsal AFO	1	4	3	3	2	2
	Ventral AFO	0	0	0	1	0	1
Walking and balance capacity assessment							
Walking aids	None	9	7	16	14	15	16
	Cane	3	1	1	1	1	1
	Quad cane	6	8	2	3	1	0
	Rolling walker	1	2	0	0	0	0
Orthoses	None	15	15	16	16	15	15
	Dorsal AFO	4	3	3	1	2	0
	Ventral AFO	0	0	0	1	0	2

AFO, convectional non-articulated ankle foot orthosis; bf, barefoot condition; s, shod condition.

Supplement 7.3.

Table of additional secondary outcomes.

Supplement 7.3. Effects of gait training assisted by multi-channel functional electrical stimulation in the experimental group compared with the control group (intention-to-treat analysis unless otherwise stated)

		Raw values[a]			Effect			
Outcome measures	G	Baseline	Post-intervention	3-month follow-up	Trans-formed data	Estimated group difference	95% CI (profile likelihood)	*p*
Step length asymmetry index – barefoot (per-protocol analysis)	E	31.0 (11.7; 63.4) (n=15)	5.5 (4.1; 17.4) (n=15)	6.9 (3.6; 14.9) (n=15)	log	-0.17	-0.64 to 0.31	.87
	C	31.8 (13.1; 78.3) (n=16)	13.2 (4.8; 21.8) (n=16)	13.4 (2.8; 23.3) (n=16)				
Step length asymmetry index – barefoot (subgroup analysis asymmetric participants)	E	46.7 (25.5; 74.4) (n=16)	14.4 (5.5; 24.8) (n=16)	9.5 (6.9; 18.5) (n=14)	log	-0.03	-0.53 to 0.48	.95
	C	51.3 (23.5; 100.0) (n=14)	13.2 (8.9; 23.0) (n=14)	13.2 (6.2; 24.5) (n=13)				
Step length asymmetry index – shod	E	22.5 (10.6; 60.8)	10.1 (2.7; 29.6)	5.8 (3.1; 15.6) (n=17)	log	-0.03	-0.56 to 0.52	.47
	C	38.6 (12.4; 79.7)	4.4 (2.7; 13.4) (n=17)	9.8 (5.1; 17.2) (n=16)				
Step time asymmetry index – shod	E	37.4 (8.0; 68.4)	17.8 (8.8; 32.7)	11.6 (6.0; 19.1) (n=17)	1+log	0.12	-0.18 to 0.41	.53
	C	37.2 (12.6; 85.2)	15.1 (3.3; 40.2)	10.8 (4.4; 19.0) (n=17)				
Single-leg stance time asymmetry index – shod	E	10.4 (5.7; 18.4)	11.9 (5.3; 19.2)	5.6 (3.6; 9.4) (n=17)	sqrt	-0.12	-0.63 to 0.39	.39
	C	10.5 (5.0; 17.1)	6.8 (3.9; 17.4)	5.9 (2.8; 14.1) (n=17)				
Stride length – shod (cm)	E	60.2 (46.3; 74.0) (n=18)	96.6 (82.1; 108.3) (n=17)	97.3 (88.8; 107.1) (n=10)	no	-1.61	-12.28 to 8.98	.46
	C	49.0 (43.3; 75.8) (n=17)	89.0 (59.4; 109.9) (n=14)	89.2 (73.7; 113.6) (n=12)				
Stride time – shod (sec)[b]	E	1.72 (1.58; 3.07) (n=18)	1.28 (1.20; 1.51) (n=17)	1.33 (1.25; 1.43) (n=10)	n.a.	n.a.	n.a.	n.a.
	C	2.14 (1.30; 4.25) (n=17)	1.35 (1.16; 1.89) (n=14)	1.32 (1.15; 1.85) (n=12)				
Berg Balance Scale (score range 0 to 56)	E	36.0 (30.5; 48.0)	54.0 (52.3; 55.0) (n=18)	56.0 (54.0; 56.0) (n=17)	n.a.	n.a.	n.a.	n.a.
	C	40.0 (21.0; 48.8)	54.0 (47.0; 55.8)	55.0 (50.0; 56.0) (n=17)				
Functional Ambulation Categories (score range 0 to 5)	E	3.0 (2.0; 4.0)	5.0 (5.0; 5.0)	5.0 (5.0; 5.0) (n=17)	n.a.	n.a.	n.a.	n.a.
	E	2.5 (2.0; 3.8)	5.0 (4.3; 5.0)	5.0 (5.0; 5.0) (n=17)				

Abbreviations: G, Group; E, Experimental group (n=19); C, Control group (n=18); log, log transformed data; sqrt, square root transformed data; n.a., not applicable.

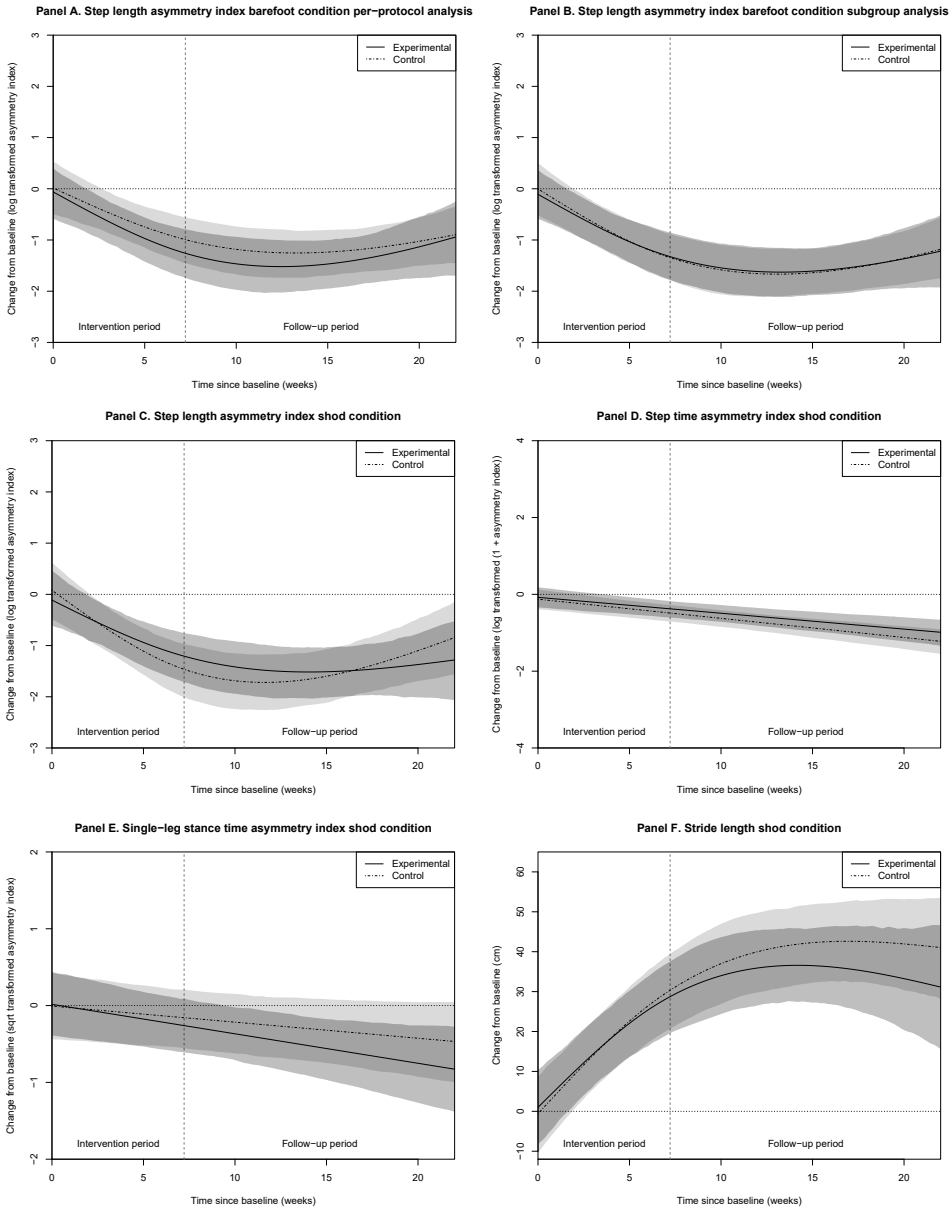
[a] Median score and 25 and 75% percentiles (data were non-normally distributed).

[b] Longitudinal analysis not applicable due to insufficient data.

Supplement 7.4.

Time trends of secondary analyses for both groups (panel A to F).

Time trends of per-protocol analysis and subgroup analysis of step length asymmetry index and time trends of asymmetry indexes and strides of the shod condition for both groups: the shaded areas indicate the 95% confidence intervals of the group means (light gray is control group, middle gray is experimental group, and dark gray is overlap between both groups). The vertical gray dashed line marks the end of the intervention period (overall mean).



Chapter 8

General discussion

"Will I ever walk like before?"

Walking is a crucial aspect in everyday life and can be severely limited by a stroke. Although almost all individuals show functional recovery in the first months post stroke, residual impairments often remain.[1,2] There are still many unanswered questions regarding the optimal treatment to enhance gait recovery after stroke.

This thesis had two general aims. First, to increase the methodological knowledge of gait assessment post stroke. And second, to determine whether gait training assisted by multi-channel functional electrical stimulation (MFES gait training) early after stroke is feasible and enhances the recovery of spatiotemporal gait symmetry and gait capacity. In this final chapter, the main findings of the presented studies in the previous chapters are critically discussed along with their implications for clinical practice. Finally, recommendations for future research are given.

Gait capacity assessment after stroke

The systematic review (Chapter 2) identified many gait capacity tests for stroke survivors that measure the categories 'short walking distance' (qualifiers 'walking distance', 'gait speed', and 'functional ambulation') and 'walking on different surfaces' of the International Classification of Functioning, disability and health (ICF). While reliability and validity were the most frequently evaluated measurement properties, it is striking that data on other measurement properties, such as responsiveness, minimal clinically important difference, and item-response theory models were lacking. The review also showed that many different measurement protocols per test were used to evaluate gait capacity. For example, the walkway distances used for the 10-Metre Walk Test and 6-Minute Walk Test varied widely (Table 2.4). In addition, the protocols were often insufficiently described. These inconsistencies complicate the transfer from scientifically evaluated gait capacity tests to proper use in clinical practice. Besides, the method of evaluation of measurement properties differed between studies. At the time the systematic review was executed, a standard methodological and statistical quality assessment was not available to evaluate measurement properties of gait capacity tests and therefore a quality assessment was composed (Chapter 2). When standardisation, descriptions, and data accessibility improve, validity and reliability of clinical use and research as well as comparability of studies increase. This is in line with the FAIR principles and the ambitions of the EQUATOR Network.[3,4]

Based on the findings from the review, the measurement properties of two promising gait capacity tests were further investigated because the measurement properties were not yet (Shuttle Walk Test, Chapter 3) or insufficiently (Functional Gait Assessment, Chapter 4) investigated. The lack of a clear Functional Gait Assessment protocol prompted to compose one with test instructions and scoring criteria to allow uniform administration and scoring which is specified for individuals with unilateral impairments (Supplement 4.1).

It was concluded that the Shuttle Walk Test and Functional Gait Assessment were valid and reliable, had no ceiling effect, and measurement error fell within acceptable ranges in a study population of independently walking stroke survivors, of which the majority were community ambulators (average gait speed above .8 m/s). Nevertheless, despite the modifications of the Functional Gait Assessment protocol, the agreement between observers on item level varied and for some items agreement was poor, possibly caused by subjective judgement (Chapter 4). Test-retest reliability was poor to moderate for six out of 10 items (Table 4.4). Although a small difference in the total score in favour of retest was found (1 point), no heteroscedasticity was present (Figure 4.2). The within-subject differences were probably due to variability.

It can be concluded from Chapters 2 to 4 that several gait capacity tests – measuring walking independency, walking balance, walking endurance, and gait speed – are appropriate for use in clinical settings and research. However, the systematic review identified no gait capacity test to assess walking adaptability (pro- and reactive stepping) for people after stroke. More recent literature also indicates that no established clinical methods to assess walking adaptability are available yet,[5,6] although recent developments are promising.[7]

Spatiotemporal gait assessment after stroke

In Chapter 5, the measurement properties of a low-cost and easy-to-use spatiotemporal gait analysis system (SGAS) were evaluated. This study showed that relevant spatiotemporal gait parameters (step and stride length and step, stride, and single-leg stance time) could be validly and reliably measured in healthy adults with the SGAS. To assess whether the SGAS is suitable for measuring spatiotemporal gait parameters in people with gait deviations, for example stroke survivors, several conditions mimicking gait deviations were measured (comfortable, slow, toe, and shod walking). The SGAS seems applicable in stroke survivors based on the excellent agreement found for the walking conditions in Chapter 5 and experiences gained in the randomised controlled trial of Chapter 7. However, the calculated minimum number of four footsteps needed to achieve an adequate level of reliability for the SGAS data may not be generalisable to individuals with gait deviations. These individuals may show rotations in the transverse plane and often show larger gait variability.

Gait variability after stroke

In the randomised controlled trial, five valid gait trials per leg were averaged to correct for gait variability (Chapters 6 and 7). However, research shows that a larger number of steps is required to perform a reliable spatiotemporal gait assessment which takes gait variability into account.[8-10] The studies in Chapters 2 to 4 also showed a relatively large measurement variability for most gait capacity tests. To correct for gait variability, at least three practice trials (for warming-up and familiarisation) should be performed and

then at least three trials should be performed and averaged.[9,10] However, this method is merely realistic for relatively short gait tests such as the 10-Metre Walk Test or SGAS. Nevertheless, the question is whether it is appropriate to disregard gait variability. Gait variability is often increased in elderly and people with neurological diseases such as stroke, and it provides valuable information on gait disturbances and regulations.[8,11] Research shows a relationship between gait variability and fall risk in elderly and individuals with neurodegenerative diseases.[12-14] In the stroke population, gait variability is often present and is associated with important aspects as fall risk, fear of falling, gait performance, and ambulatory activity.[15-17] Gait variability was not taken into account in the gait capacity tests (Chapters 2 to 4) nor in many studies evaluating the gait pattern (among which the studies described in this thesis). However, because gait variability provides additional information about the fluctuations/inconsistency of the gait pattern and may be more sensitive to change than the mean values, assessing both the mean value and variability of gait parameters is recommended.[18,19] To evaluate the variability of spatiotemporal gait parameters post stroke, the standard deviation seems the preferred estimator.[18] This estimator appears most responsive to changes of temporal parameters, compared to the coefficient of variation and median absolute deviation.[18] Furthermore, the (Enhanced) Gait Variability Index can be used, which combines the mean values and standard deviations of several spatiotemporal gait parameters into one generic, conglomerate measure to evaluate changes of the gait pattern compared to a reference group.[19-22]

Gait recovery early after stroke

Daily 30-minute sessions of MFES gait training – MFES applied to the peroneal nerve and thigh muscle (knee flexor or extensor muscle) – for up to 10 weeks during inpatient rehabilitation appeared to be feasible (Chapters 6 and 7). However, findings from this pilot randomised controlled trial did not demonstrate a beneficial effect of MFES gait training compared to conventional gait training on the recovery of step length symmetry (the primary outcome) or secondary outcomes (spatiotemporal gait parameters and gait capacity).

Improving post-stroke leg motor recovery is important to improve gait quality.[23] However, although several intervention studies suggest superiority of specific training interventions, to date, neither animal nor human studies have shown that training interventions can restore leg motor control.[24,25] Three possible explanations for the lack of proof of benefit may be: (1) clinical heterogeneity among stroke survivors included in intervention studies may have masked possible efficacy in selected subsets of people after stroke (false-negative trials); (2) training interventions in an everyday clinical setting may not improve motor recovery of the affected leg; and/or (3) training interventions may not enhance restitution of leg motor function. This reasoning is discussed in more detail in the next three paragraphs.

The stroke population is heterogeneous with respect to initial neurological deficits

and recovery potential, which is a possible contributor to the negative outcomes of intervention trials.[25-28] If subsets of stroke survivors with the potential to recover from a specific intervention can be identified, we might be able to show superiority of specific training interventions for subgroups of stroke survivors.[25,27,28] Appropriate biomarkers of post-stroke plasticity are needed to help understand who should be treated and when.[28] Great advances have been made in understanding the biological basis of neurological and functional recovery post stroke in animal studies.[28] However, translation into human studies has been slow.[28] To achieve progress, mechanistic studies to understand post-stroke plasticity mechanisms must move towards research in humans after stroke.[28]

A second explanation for the lack of proof of benefit may be that the intensity and dose of the current training interventions in clinical practice are insufficient. Achieving effects on leg motor control may need much higher training dose (frequency, duration, and intensity) than that are feasible in clinical practice (25 hours training per week or more for several weeks were suggested for the upper extremity).[28,29] However, it is questionable whether such high doses are realistic, especially for the lower extremity, because of the challenging logistics of setting up high-dose and high-intensity intervention trials in (low-dose) clinical practice.[28,29]

Regardless of dosage and intensity, it remains a fundamental question whether the restitution of motor control can be enhanced merely through training interventions (third explanation for the lack of proof of benefit). Functional recovery after stroke is the result of either true neurological recovery of sensorimotor functions (*restitution* of function) or the learning of new sensorimotor compensatory strategies (*substitution* of function).[24] In the context of gait, true recovery refers to the restitution of pre-stroke gait patterns while compensation refers to the use of adjusted gait patterns.[30] The discrimination between recovery and compensation is increasingly highlighted in stroke rehabilitation, even leading to discussions on whether allowing compensatory strategies early post-stroke might prevent the possibility of true recovery.[24,31] Yet, in view of the current evidence, it appears that rehabilitation promotes largely (and possibly entirely) the substitution of function.[1,32-36] The results of longitudinally conducted studies in the stroke population favour the use of adaptive, compensatory movement strategies and the use of synergy-dependent motor control to restore gait capacity.[1,32-34] However, even at the capacity level, recovery through *training interventions* is only possible to a limited extent depending on the individual's physical fitness, cognitive functioning and, of course, on the degree of spontaneous neurological sensorimotor recovery.[37-40] To further optimise compensatory adaptations early post stroke, the course of functional gait recovery should be monitored and *medical-technical interventions* such as orthotics, orthopaedic footwear, assistive walking devices, orthotic functional electrical stimulation (FES), focal spasmolytic treatment, and surgery should be timely prescribed.[41-43]

By supporting paretic leg muscles through MFES early post stroke, it was hypothesised that this training intervention could potentially improve the restitution and/or substitution

of motor functions (Chapters 6 and 7). Step length symmetry was chosen as the primary outcome because it is the sum of diverse kinetic and kinematic aspects of the gait pattern and this outcome measure does not seem to be related to factors such as age and time post stroke (in contrast to gait speed).[44,45] It was a well-considered choice to select a generic outcome measure for expressing normalisation of the gait pattern in stroke survivors, as MFES assists muscle activity of the paretic leg and the MFES positioning and stimulation parameters were individualised.[46] Furthermore, by imposing adequate movements of the paretic leg in the early phase post stroke, an attempt was made to prevent 'learned non-use'.[24,47] However, based on the results of our pilot randomised controlled trial (Chapter 7) and on the literature on leg motor recovery, it is questionable whether training interventions can promote restitution of function. In this perspective, the goal of achieving gait symmetry can be questioned.[48-51] Indeed, gait asymmetry can be seen as a positive compensatory adaptation (substitution of function) to the neurological deficits caused by stroke.[52] Seen from this point of view, asymmetric gait may be important to recover gait speed and promote requirements for forward progression.[48] Nevertheless, given the potential long-term consequences of persisting gait asymmetry (i.e. increased risk of falls and injuries, reduced gait efficiency, poor aesthetics, risk of muscle shortening, joint deformation, and pain complaints), attention to gait symmetry remains clinically important.[53-57] Based on the current evidence, attempts to improve gait symmetry can best be made by combining medical-technical interventions with targeted training.[41,58]

Methodological considerations

Transparent research integrated in clinical practice after stroke

A major advantage of the studies as reported in Chapters 3 to 7 is that they have been conducted in a real-world everyday clinical setting. Furthermore, all studies have been performed and described according to international guidelines (i.e. CONSORT, SPIRIT, and PRISMA).[4] The pilot randomised controlled trial was registered in the Netherlands Trial Register and a design article (Chapter 6) was published before the inclusion of participants was finished. This pragmatic and transparent approach improves the generalisability and implementation of the study results into clinical practice.

Limitations in the study designs regarding gait assessment

Despite the recommendation from Chapter 2 to include responsiveness, minimal clinically important difference, and item-response theory models in the assessment of measurement properties of gait capacity tests, these aspects were not investigated in the studies described in Chapters 3 and 4. For the Shuttle Walk Test, this was the first study investigating its measurement properties in stroke survivors, justifying the choice to start with the evaluation of validity, reliability, and measurement error (Chapter 3). Evidence

already existed for the validity and reliability of the Functional Gait Assessment in people after stroke.[59,60] Investigation of the responsiveness, minimal clinically important difference, and item-response theory of the Functional Gait Assessment would have increased the value of this study for the interpretation of the test results, in particular for evaluating the efficacy of interventions (e.g. Chapter 7). One study investigated the item-response theory of the Functional Gait Assessment in elderly and concluded that the current order of items is sufficient.[61] Nevertheless, future research should determine item discrimination and item difficulty of the Functional Gait Assessment specifically for the stroke population.

The burden of study participation for the in- and outpatients in the sub-acute phase after stroke, was high in two of the studies (Chapter 4 and Chapters 6 and 7). For pragmatic reasons, the assessments in the study described in Chapter 4 were frequently planned on the same day, in the morning and afternoon. This program was intensive for the participants and could have had a negative impact on the results of the assessments performed in the afternoon and, therefore, could have negatively influenced the minimal detectable difference and test-retest reliability. In order to restrict the negative effect of this limitation, the participants did not receive physiotherapy on the day of assessment and they were advised to rest in between sessions. In Chapter 6, the design of a proof-of-principle study with an explorative character was described (Figure 6.1 illustrates the extensive list of measurement instruments). The burden on participants was considerable (one participant dropped out for this reason), while not all data was used for the results section of Chapter 7. On the other hand, only five valid gait trials per leg were collected to evaluate the spatiotemporal gait parameters (without the use of standardised practice trials) to minimise the burden on participants. Based on the literature, this number of five trials is considered too small to obtain a reliable measurement.[8-10] The impact of this choice remains unknown, but it can be concluded that – by preferring completeness of data collection – accuracy of data may have been decreased.[62]

Treatment fidelity of gait training assisted by MFES

The MFES application procedure, as described in Chapters 6 and 7, is complex. A strength of the study design is that the MFES intervention was individually tailored, which is common practice in clinical care, but not in scientific research. However, the individualised positioning of the MFES device and parameter setting increased the complexity of the MFES fitting procedure and led to a certain form of methodological ‘black box’. Due to the diversity of MFES positioning and parameter settings, the effects of specific MFES settings could not be assessed. This consequence is inherent in the necessity to apply MFES as a personalised intervention.

Furthermore, both the authorised clinicians (who fitted and set the MFES device) and physiotherapists (who carried out the gait training) involved in the pilot randomised controlled trial (Chapters 6 and 7) experienced complexity of the application of MFES. The MFES fitting procedure was carried out by two authorised clinicians per session (despite

the fact that the study protocol prescribed one). The devices were fitted at a low frequency during the long inclusion period and the trained, authorised clinicians felt insecure about performing this procedure. Therefore, two authorised clinicians carried out the procedure to increase the reliability of the setting process. This indicates that experience and regular repetition are required. Contrary to our expectations, fine-tuning of the MFES setting parameters was not necessary during the intervention period for most participants in the experimental group.[63] After a while, the MFES setting evaluation sessions were sometimes used as regular training sessions, when it was thought that no adjustments would be necessary. An interesting question is whether the relative lack of routine of the authorised clinicians was anyhow related to the limited experienced need they felt for individual fine-tuning of the MFES settings during the intervention period. The importance of knowledge of and experience with MFES application was also explicitly stated by the physiotherapists who gave the MFES gait training. Instead of a predicted two years inclusion period, it took four years to include 40 participants, which did not benefit the knowledge and experience with the MFES devices. Both the authorised clinicians and the physiotherapists were trained before the study onset, but periodic repetition of training seems important. The effect of lack of routine on the study results remains unclear, but MFES is not easy-to-use and requires time, experience, and expertise.

Clinical implications

Gait capacity assessment in stroke rehabilitation

Assessment in clinical practice should serve to substantiate treatment choices and to evaluate treatment. From the review presented in Chapter 2, the Functional Ambulation Categories, 10-Metre Walk Test, and 6-Minute Walk Test are advised to measure different aspects of gait capacity. The Functional Ambulation Categories provide insight in walking independence. From up to Functional Ambulation Categories score 3 (walking under supervision or independently), the other measurement instruments become relevant to administer. Gait speed is preferably assessed by the 10-Metre Walk Test, because this test is easy to administer and most studies have used this test as the outcome measure for assessing gait speed. Moreover, it is recommended in a recent study promoting a consensus-based core set for clinical motor rehabilitation after stroke.[64,65] It is sufficient to measure comfortable gait speed, because research has shown that the maximum gait speed can reliably be estimated based on the comfortable gait speed.[66] Gait speed on parquetry is a strong predictor of gait speed on carpet measured by the 6-Metre Walk Test.[67] Therefore, it is questionable whether this test measures the ICF category ‘walking on different surfaces’ adequately. The 6-Minute Walk Test measures the ICF category ‘walking short distances’. Evaluation of gait speed using the 6-Minute Walk Test is also relevant as a decrease in gait speed over time has been demonstrated.[68] Combining the

above with the results of Chapters 3 and 4, the Functional Gait Assessment and Shuttle Walk Test are advised to measure the qualifier 'functional ambulation' and the category 'long walking distance' of the ICF (the latter only in case of community ambulators). As the Functional Gait Assessment includes measures of gait balance, it should be used in addition to the Functional Ambulation Categories (from up to Functional Ambulation Categories score 3). The Shuttle Walk Test and 6-Minute Walk Test can both be seen as proxy measures of cardiorespiratory fitness.[69,70] Authors reported a good correlation within each test between the VO_2 peak and the performance outcome of the Shuttle Walk Test (shuttles) and 6-Minute Walk Test (metres).[70] However, a moderate correlation was found between both tests and an incremental cycle test on an ergometer for VO_2 peak.[70] The Shuttle Walk Test is relevant to community ambulators who can walk with a gait speed ≥0.8 m/s and is suitable for group programs such as circuit class training or sports rehabilitation programs (the 6-Minute Walk Test can then be omitted). In low-speed walkers (gait speed <0.8 m/s) the 6-Minute Walk Test is the better alternative (Chapter 3).

As consistent protocols for assessing gait capacity are lacking in the literature (Chapters 2 and 4), it is recommended to document agreements within a clinical setting about the test instructions and administration procedure of gait capacity tests by Standard Operating Procedures in order to increase inter-rater reliability.[71]

One should be careful when evaluating an individual's gait capacity progress over time or when evaluating individual effects of treatment, since evidence on responsiveness and the minimal clinically important difference of most measurement instruments are lacking (Chapter 2). Based on the available evidence, one can speak of a true change when the difference between two assessments is greater than the measurement error (which has been adequately reported for most gait capacity tests in one or more studies described in Chapter 2). In addition, it is recommended to add a patient reported outcome measure to evaluate change over time and relevant goals from the individuals' perspective (e.g. Goal Attainment Scaling,[72] Canadian Occupational Performance Measure,[73] or Stroke Impact Scale[64]).

Spatiotemporal gait assessment in stroke rehabilitation

In clinical practice, information about relevant post-stroke spatiotemporal gait parameters (step and stride length, step time, stride width, double support time, step length symmetry, and cadence) is mostly obtained by non-quantified visual gait observation in real-time or from two-dimensional video assessments.[74-77] However, this method produces subjective, error-prone information that cannot be accurately evaluated.[76] Furthermore, literature shows that gait patterns and the responses to interventions vary widely and that two-thirds of the treatment plans are adapted as a result of instrumented gait analysis, which demonstrates the importance of a valid evaluation of the gait pattern by quantified data.[78,79] Therefore, it is highly recommended to obtain quantified spatiotemporal gait parameter data by easy instrumented gait analysis methods, such as the SGAS.[80-93]

The selection of spatial and/or temporal parameters can be based on the limitations within the five gait prerequisites (stance phase stability, swing phase clearance, foot preposition in terminal swing, adequate step length, and energy conservation) as proposed by Gage[94] or the specific aim of an intervention. Table 8.1 illustrates a proposed classification of the most common spatiotemporal gait parameters categorised according to the five prerequisites.

Table 8.1. Classification of relevant common spatiotemporal gait parameters based on the five gait prerequisites of Gage[94]

Stance stability	Ipsilateral single-leg stance time Contralateral step length Contralateral step time Double support time Stride width Temporal gait symmetry Step length symmetry
Clearance	Ipsilateral step time Ipsilateral step length Double support time Temporal gait symmetry Step length symmetry
Foot prepositioning	Ipsilateral step length Ipsilateral step time Stride width Double support time Step length symmetry Temporal gait symmetry
Step length	Ipsilateral step length Stride length Step length symmetry
Energy conservation	Walk ratio (step length/cadence) Stride length Stride time Temporal gait symmetry Step length symmetry Cadence (steps/minute) Stride width

The role of MFES in gait training early after stroke

Based on the inconclusive evidence from randomised controlled trials on the therapeutic effects of FES, currently it is not advisable to use MFES in stroke rehabilitation, awaiting further studies on its efficacy in subgroups of stroke survivors.[95-106] This advice is based on four arguments: (1) there is no conclusive evidence for superior efficacy of MFES gait training compared to conventional gait training; (2) the investment costs of MFES are relatively high; (3) sufficient expertise in the application of MFES is not easily achieved; and (4) MFES device positioning and parameter setting are time consuming. This does not preclude the orthotic application of FES in stroke rehabilitation, since superior efficacy

of orthotic FES has been shown compared to no intervention for people with drop foot after stroke.[58,95,96,101,107] Although recent literature suggests that FES is preferred by many of its users,[100,101,108-116] orthotic FES seems to be equally effective compared to ankle foot orthoses for improving gait-related outcomes in people with drop foot after stroke.[100,114,116-120] Interestingly, a recent study has suggested superior efficacy of (implanted) peroneal FES compared to an ankle foot orthosis for improving gait adaptability in chronic stroke survivors.[121] This result needs to be confirmed by future (controlled) studies before it can be clinically implemented.

Future research

Standardisation, interpretation, and evaluation of gait assessment after stroke

Based on the aspects covered in this general discussion, important future steps in the scientific evaluation of measurement properties of gait tests in the stroke population are: (I) the standardisation of gait capacity testing protocols; (II) the standardisation of study design and reporting; (III) attention to the measurement properties responsiveness, minimal clinically important difference, and item-response theory models; (IV) improvement of the accessibility of raw data; (V) integration of variability parameter outcomes in appropriate gait tests (e.g. 10-Metre Walk Test and SGAS); (VI) evaluation of validity and reliability of the SGAS in stroke survivors by using three-dimensional gait analysis as (golden) reference; and (VII) development and evaluation of gait capacity tests assessing the ICF categories 'walking long distances (>1 km)', 'walking around obstacles', 'walking on different surfaces', and 'walking adaptability'.[20] Furthermore, an update of our systematic review (Chapter 2) is recommendable since, after its publication in 2012, only one new review was published on timed gait tests in 2017.[122]

Gait training assisted by FES early after stroke

Literature on the efficacy of FES gait training during early stroke rehabilitation is inconclusive and therefore more research in homogenous study populations is warranted to draw definite conclusions. Some recommendations regarding future research can be made.

First, future studies should investigate whether a targeted group of stroke survivors may benefit from this treatment.[27,28] Based on the current literature it is difficult to recommend a certain profile of responders to MFES gait training. Two studies described the following factors for stroke survivors who may benefit most from peroneal FES for improving gait speed: female,[123] younger age,[124] higher number of interventions,[123] greater baseline active ankle dorsiflexion,[123] and greater baseline mobility levels.[124] Furthermore, development of prognostic models for predicting leg motor recovery can support the selection of potential responders to treatment.[27]

Second, it is recommended to investigate whether a FES device stimulating the gastrocnemius muscle during the late stance phase of the gait cycle can improve paretic leg propulsion and, thereby, gait symmetry.[125] Indeed, many stroke survivors deal with gait impairments related to a decreased power from the ankle plantarflexors.[52,126-128] Several studies recommend targeting paretic leg propulsion to improve gait after stroke.[127-130]

Third, the efficacy of FES beyond the supervised gait training sessions should be investigated. An advantage of FES is that it increases the unsupervised exercise opportunities. There is growing evidence for the efficacy of high-intensity and task-specific training to improve gait capacity after stroke.[28,131-134] Many studies fail to intensify training sufficiently, which is related to the current time-limited rehabilitation programs.[28] Which intensity of training is optimal is unknown,[132-134] although there are some studies providing information.[29,135,136] FES can increase the intensity and task-specificity of independent exercise beyond the supervised therapy sessions.

Finally, investigation of the efficacy of combining orthotic FES application and training interventions to improve gait capacity in early stroke rehabilitation is recommended. By introducing a structural change of the gait pattern by FES, room for improvement of gait capacity and gait performance may be created.

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Summary

Many stroke survivors suffer from walking limitations that may persist long after stroke onset. These walking limitations result in reduced functional mobility and community ambulation, and an increased fall risk. Therefore, regaining independent and safe gait capacity is one of the most important goals early after stroke. Most stroke survivors with limited gait capacity suffer from leg muscle weakness and disrupted timing and regulation of muscle activation resulting in asymmetric gait. An asymmetric gait pattern forms a risk of overloading the trunk and the non-paretic side and is associated with limited gait adaptability, increased risk of falls and injuries, fear of falling, and reduced gait efficiency, gait speed, physical activity, and aesthetics of walking. Furthermore, persisting gait asymmetry may predispose stroke survivors to the development of other musculoskeletal problems, such as muscle shortening, joint deformation, and pain complaints. Interventions targeting gait asymmetry early after stroke may improve the recovery of walking. Functional electrical stimulation has been used to improve gait capacity, but evidence is mostly limited to the orthotic effects of peroneal functional electrical stimulation in the chronic phase after stroke. Multi-channel functional electrical stimulation (MFES) applied to the peroneal nerve and knee flexor or extensor muscles might improve spatiotemporal gait symmetry by compensating for thigh and dorsiflexion muscle weakness. To this end, objectifying the effects of an intervention by instruments with adequate measurement properties is required. The present thesis had two general aims. First, to increase the methodological knowledge of gait assessment post stroke. And second, to determine whether gait training assisted by MFES early after stroke is feasible and enhances the recovery of spatiotemporal gait symmetry and gait capacity. Both topics are introduced in *Chapter 1*.

Walking tests with adequate measurement properties are required to evaluate treatment benefits of gait training interventions, to guide clinical decision making, and to monitor individual progress. *Chapter 2* describes the results of a systematic review on the measurement properties of walking tests applied to stroke survivors to assess gait capacity. Thirty-two studies, evaluating 23 walking tests, were included. These tests assessed four walking domains: short walking distance (≤1 km), walking speed, functional ambulation, and walking on different surfaces. No studies were found assessing the domains of walking long distances (>1 km) or negotiating obstacles. Within the various domains, the 6-Minute Walk Test (short walking distance), the 10-Metre (comfortable and fast) Walk Test (walking speed), the Functional Ambulation Categories (functional ambulation), and the 6-Metre Walk Test on parquet and carpet (walking on different surfaces) were most often studied. The included studies reported that most walking tests are valid, reliable, and feasible for use in stroke survivors. However, data on responsiveness, measurement error, minimal detectable change, and minimal clinically important difference are lacking. This review may serve as a guide to clinicians and researchers for choosing the optimal walking test given a specific measurement aim.

Chapter 3 reports on a cross-sectional study determining the construct validity, test-retest reliability, and measurement error of the Shuttle Walk Test, measuring functional gait capacity of persons after stroke. A convenience sample of 75 persons after stroke were included who were capable of walking without physical assistance. Construct validity was assessed by (1) testing the association between the walking distance obtained with the Shuttle Walk Test and that with the commonly used 6-Minute Walk Test and (2) testing the differences in increment of heart rate and rate of perceived exertion between the two walking tests. Difference scores were significantly higher for the Shuttle Walk Test than for the 6-Minute Walk Test in community ambulators (gait speed mean ≥0.8 m/s). In the small group (n=12) of low-speed walkers (gait speed mean <0.8 m/s), no significant correlations or differences between tests were found except for a significantly different walking distance. These participants walked a longer distance on the 6-Minute Walk Test. Test-retest reliability was examined by repeating the Shuttle Walk Test twice within one week and was indicated as good. Measurement error, determined with the standard error of measurement, and minimal detectable change were within acceptable ranges. These results suggest that the Shuttle Walk Test is a valid and reliable measure and, therefore, a feasible instrument to determine functional gait capacity of persons after stroke, especially in community ambulators.

Chapter 4 describes the construct validity and reproducibility of the Functional Gait Assessment for measuring walking balance capacity in persons after stroke. Fifty-two persons after stroke, receiving in- or outpatient rehabilitation, with independent gait capacity completed a standardised Functional Gait Assessment twice within one to eight days by the same investigator. Validity was evaluated by testing hypotheses on the association with two timed walking tests, with the Berg Balance Scale, with the mobility domain of the Stroke Impact Scale, and with the Functional Ambulation Categories. Construct validity was good: 80% of the hypotheses could be confirmed. Reproducibility was evaluated by determining the inter-rater, intra-rater, and test-retest reliability of the total scores and found to be excellent. The standard error of measurement and minimal detectable change were within acceptable ranges. The Functional Gait Assessment demonstrated good measurement properties in persons after stroke and yielded no ceiling effect in contrast to other capacity measures.

Chapter 5 reports a cross-sectional study determining the concurrent validity and reliability of a low-cost spatiotemporal gait analysis system (SGAS) for clinical use and research purposes. The SGAS consists of a camera placed perpendicular to a walkway, which can be used stationary or moved manually along a parallel rail system to capture multiple strides of an individual during a single walk. Thirty-three healthy adults participated in this study. The conditions evaluated were barefoot walking at comfortable and slow speed, toe and shod walking using a stationary camera setup, and barefoot walking at comfortable speed using a moving camera setup. The GAITRite® system was used as a reference. The SGAS proved to be valid to asses step length, stride length, step

time, stance time, and stride time, across setups and conditions. The standard error of measurement and Bland-Altman repeatability coefficients were within acceptable ranges (<5% and <8% of the weighted mean, respectively). A minimum of four footsteps in case of a stationary camera is recommended to obtain reliable estimates of each of the parameters tested. It is concluded that the SGAS is valid and reliable for assessing spatiotemporal gait parameters. However, the validity for assessing double support time and swing time could not be confirmed.

Chapter 6 describes the study protocol of a single-centre pilot randomised controlled trial on the feasibility and preliminary efficacy of up to 10 weeks of MFES gait training in early stroke rehabilitation to enhance recovery of spatiotemporal gait symmetry and gait capacity. Forty adult participants with walking deficits, who were admitted for inpatient rehabilitation within 31 days since the onset of stroke, were randomised to either MFES gait training or conventional gait training. Gait training was delivered in 30-minute sessions each workday for up to 10 weeks. MFES was applied to the peroneal nerve and one thigh muscle (knee flexor or extensor muscle depending on which gait aspect was inadequate and had priority to be improved) to assist gait during training. Blinded assessors conducted outcome assessments at baseline, every two weeks during the intervention period, immediately post intervention, and at 3-month follow-up. Step length asymmetry index, representing the step length difference between the paretic and non-paretic leg, served as the primary outcome and secondary outcomes included spatiotemporal gait parameters measured by the SGAS (i.e. step time, stance time, and its asymmetry indexes) and gait capacity measures (i.e. gait speed and walking balance). Feasibility was determined by adherence to training sessions and satisfaction with gait training. Primary efficacy analysis was performed on an intention-to-treat basis using linear mixed models to estimate treatment effects post-intervention and at 3-month follow-up.

The results of the pilot randomised controlled trial are presented in *Chapter 7*. The intervention period was completed by 19 participants in the experimental group (receiving MFES gait training) and 18 participants in the control group (receiving conventional gait training). This study confirmed the feasibility of MFES gait training, but could not demonstrate any difference between MFES gait training and conventional gait training with regard to the primary or secondary outcomes. Both groups demonstrated comparable improvements on all primary and secondary outcomes. Though limited by a small sample size, the results suggest that MFES gait training is feasible but may not be superior to conventional gait training to enhance the recovery of spatiotemporal gait symmetry, spatiotemporal gait parameters, or gait capacity in a representative stroke population during early rehabilitation. However, this conclusion does not preclude possible beneficial effects of MFES gait training in a more targeted population with better potential for the restoration of spatiotemporal gait symmetry.

In the final chapter, *Chapter 8*, the main findings of this thesis are reviewed and some methodological considerations are addressed. The results of studies are put into clinical perspective and recommendations for future research are made. First, it was concluded that several valid and reliable tests are available to measure different aspects of gait capacity and spatiotemporal gait parameters in stroke survivors with gait deficits. Information on measurement properties – responsiveness, minimal clinically important difference, and item-response theory models – was lacking and should be investigated. In addition, it is recommended to collect data of a large number of strides to evaluate spatiotemporal gait parameters and add a measure of gait variability for clinical use and research as it provides valuable information on gait disturbances, related aspects such as fall risk, and may be more sensitive to change than mean gait values. Second, the results of the pilot randomised controlled trial (Chapter 7) seem to be in line with findings in the literature; no superior effect of any training intervention has been shown on enhancing leg motor control post stroke. These outcomes favour the use of adaptive, compensatory movement strategies to improve gait capacity by training combined with medical-technical interventions (e.g. orthotics, focal spasmolysis, and orthopaedic surgery). Currently, there seems to be insufficient evidence to recommend MFES as part of gait training after stroke. Future larger studies in the field of early stroke rehabilitation should investigate whether a more targeted group may benefit from this treatment, whether electrical stimulation of the gastrocnemius muscle during the late stance phase of the gait cycle can improve paretic leg propulsion, and whether unsupervised or orthotic use of MFES enhances the recovery of gait capacity and performance.

Samenvatting

Veel mensen die een beroerte hebben doorgemaakt, hebben loopbeperkingen die nog lang na het begin van een beroerte kunnen bestaan. Deze loopbeperkingen resulteren in verminderde functionele mobiliteit en vormen een verhoogd valrisico. Daarom is het herstellen van een onafhankelijke en veilige loopcapaciteit één van de belangrijkste doelen vroeg na een beroerte. De meeste mensen die na een beroerte een beperkte loopcapaciteit hebben, hebben last van zwakte van de beenspieren en een verstoorde timing en regulatie van spieractivatie, wat resulteert in een asymmetrisch looppatroon. Een asymmetrisch looppatroon vormt een risico op overbelasting van de romp en de niet-paretische zijde en wordt geassocieerd met een beperkt aanpassingsvermogen van het looppatroon, een verhoogd risico op vallen en verwondingen, valangst en een verminderde loopefficiëntie, loopsnelheid, fysieke activiteit en loopesthetiek. Daarnaast kan aanhoudende loopasymmetrie mensen na een beroerte vatbaar maken voor de ontwikkeling van andere musculoskeletale problemen, zoals spierverkorting, gewrichtsdeformatie en pijnklachten. Interventies die gericht zijn op vermindering van de asymmetrie van het looppatroon vroeg na een beroerte kunnen het herstel van lopen mogelijk verbeteren. Functionele elektrische stimulatie wordt gebruikt om de loopcapaciteit te verbeteren, maar het formele bewijs blijft beperkt tot de orthetische effecten van peroneale functionele elektrische stimulatie in de chronische fase na een beroerte. Multi-kanaal functionele elektrische stimulatie (MFES) toegepast op de peroneale zenuw en knieflexoren of -extensoren zou de spatiotemporele symmetrie van het lopen kunnen verbeteren door compensatie van zwakte van de dijbeenspieren en enkeldorsaalflexoren. Daartoe is het objectiveren van de effecten van een interventie door middel van instrumenten met adequate meeteigenschappen vereist. Dit proefschrift had twee algemene doelstellingen. Ten eerste de methodologische kennis van loopmetingen na een beroerte te vergroten. En ten tweede bepalen of looptraining, ondersteund door MFES, vroeg na een beroerte haalbaar is en het herstel van spatiotemporele loopsymmetrie en loopcapaciteit verbetert. Beide onderwerpen worden geïntroduceerd in *hoofdstuk 1*.

Looptesten met adequate meeteigenschappen zijn nodig om de behandelvoordelen van looptraining te evalueren, om klinische besluitvorming te ondersteunen en om individuele vooruitgang te monitoren. *Hoofdstuk 2* beschrijft de resultaten van een systematische literatuurstudie naar de meeteigenschappen van testen die zijn toegepast bij mensen na een beroerte om de loopcapaciteit te beoordelen. Tweeëndertig studies, die 23 looptesten evalueerden, werden opgenomen. Deze testen beoordeelden vier loopdomeinen: korte loopafstand (≤1 km), loopsnelheid, functionele loopactiviteit, en lopen op verschillende ondergronden. Er werden geen studies gevonden die de domeinen van het lopen over lange afstanden (>1 km) of het ontwijken van obstakels beoordeelden. Binnen de verschillende domeinen zijn de 6-Minute Walk Test (korte loopafstand), de 10-Metre (comfortabele en snelle) Walk Test (loopsnelheid), de Functional Ambulation Categories (functioneel lopen) en de 6-Metre Walk Test op parket en tapijt (lopen op verschillende ondergronden) het

vaakst bestudeerd. De geïncludeerde onderzoeken meldden dat de meeste looptesten valide, betrouwbaar en uitvoerbaar zijn voor gebruik bij mensen na een beroerte. Gegevens over responsiviteit, meetfout, minimale waarneembare verandering en minimaal klinisch relevant verschil ontbreken echter. Deze literatuurstudie kan dienen als leidraad voor clinici en onderzoekers bij het kiezen van de optimale looptest voor een specifiek meetdoel.

Hoofdstuk 3 rapporteert een cross-sectionele studie die de constructvaliditeit, test-hertestbetrouwbaarheid en meetfout van de Shuttle Walk Test bepaalt, waarmee de functionele loopcapaciteit van personen na een beroerte wordt gemeten. Een steekproef van 75 personen na een beroerte werd geïncludeerd die in staat was om zonder fysieke begeleiding te lopen. De constructvaliditeit werd beoordeeld door (1) het testen van de associatie tussen de loopafstand verkregen met de Shuttle Walk Test en die met de veelgebruikte 6-Minute Walk Test en (2) het testen van de verschillen in toename van de hartslag en de mate van ervaren inspanning tussen de twee looptesten. De verschilscores waren significant hoger voor de Shuttle Walk Test dan voor de 6-Minute Walk Test voor ambulante personen (loopsnelheid gemiddeld ≥0,8 m/s). In de kleine groep (n=12) langzame lopers (loopsnelheid gemiddeld <0,8 m/s) werden geen significante correlaties of verschillen tussen de testen gevonden, behalve een significant verschillende loopafstand. Deze deelnemers liepen een langere afstand tijdens de 6-Minute Walk Test. De test-hertestbetrouwbaarheid was onderzocht door de Shuttle Walk Test binnen een week twee keer uit te voeren en werd als goed beoordeeld. De standaard meetfout en de minimale waarneembare verandering lagen binnen aanvaardbare marges. Deze resultaten suggereren dat de Shuttle Walk Test een valide en betrouwbaar meetinstrument is en daarom een uitvoerbaar instrument om de functionele loopcapaciteit van personen na een beroerte te bepalen, in het bijzonder bij relatief goede lopers.

Hoofdstuk 4 beschrijft de constructvaliditeit en reproduceerbaarheid van de Functional Gait Assessment voor het meten van loopbalanscapaciteit bij personen na een beroerte. Tweeënvijftig personen met onafhankelijke loopcapaciteit na een beroerte, die klinische of poliklinische revalidatie ontvingen, voltooiden tweemaal binnen één tot acht dagen een gestandaardiseerde Functional Gait Assessment door dezelfde onderzoeker. Validiteit werd geëvalueerd door hypothesen te testen over de associatie met twee getimede looptesten, met de Berg Balance Scale, met het mobiliteitsdomein van de Stroke Impact Scale, en met de Functional Ambulation Categories. De constructvaliditeit was goed: 80% van de hypothesen kon worden bevestigd. De reproduceerbaarheid werd beoordeeld door het bepalen van de interbeoordelaars-, intrabeoordelaars- en test-hertestbetrouwbaarheid van de totaalscores en bleek uitstekend te zijn. De standaard meetfout en minimale waarneembare verandering waren binnen acceptabele marges. De Functional Gait Assessment toonde goede meeteigenschappen bij personen na een beroerte en had geen plafondeffect in tegenstelling tot andere capaciteitsmeetinstrumenten.

Hoofdstuk 5 rapporteert een cross-sectionele studie die de concurrente validiteit en betrouwbaarheid bepaalt van een goedkoop spatiotemporeel ganganalysesysteem

(SGAS) voor klinisch gebruik en onderzoeksdoeleinden. De SGAS bestaat uit een camera die loodrecht op een loopbaan is gepositioneerd en die stationair kan worden gebruikt of handmatig langs een parallel railsysteem kan worden bewogen om meerdere stappen van een persoon tijdens een enkele loopafstand vast te leggen. Drieëndertig gezonde volwassenen namen deel aan dit onderzoek. De geëvalueerde condities waren blootsvoets lopen op comfortabele en lage snelheid, lopen op de tenen en met schoeisel, met een stilstaande cameraopstelling, en blootsvoets lopen op comfortabele snelheid met behulp van een bewegende cameraopstelling. Het GAITRite® systeem werd als referentie gebruikt. De SGAS bleek valide te zijn om staplengte, schredelengte, stapduur, standduur en schrededuur te beoordelen voor de verschillende cameraopstellingen en loopcondities. De standaard meetfout en Bland-Altman herhaalbaarheidscoëfficiënten lagen binnen aanvaardbare marges (respectievelijk <5% en <8% van het gewogen gemiddelde). Een minimum van vier voetstappen in het geval van een stationaire camera wordt aanbevolen om betrouwbare schattingen van elk van de geteste parameters te verkrijgen. We concludeerden dat de SGAS valide en betrouwbaar is voor het beoordelen van spatiotemporele loopparameters. De validiteit voor het beoordelen van dubbele standduur en zwaaiduur kon echter niet worden bevestigd.

Hoofdstuk 6 beschrijft het onderzoeksprotocol van een pilot gerandomiseerde gecontroleerde studie op één onderzoeklocatie naar de uitvoerbaarheid en preliminaire werkzaamheid van maximaal 10 weken MFES looptraining in de vroege revalidatie na een beroerte om het herstel van spatiotemporele gangsymmetrie en loopcapaciteit te verbeteren. Veertig volwassen deelnemers met loopproblemen, die binnen 31 dagen na het begin van de beroerte werden opgenomen voor klinische revalidatie, werden gerandomiseerd naar ofwel MFES-looptraining of conventionele looptraining. Looptraining werd gedurende maximaal 10 weken elke werkdag gegeven in sessies van 30 minuten. MFES werd toegepast op de nervus peroneus en één dijbeenspier (knieflexor of -extensor, afhankelijk van welk loopaspect onvoldoende was en prioriteit had om te worden verbeterd) om het lopen tijdens de training te ondersteunen. Geblindeerde beoordelaars voerden metingen uit bij de start (baseline), elke twee weken tijdens de interventieperiode, onmiddellijk na de interventie, en na drie maanden vervolgen van de deelnemers. De staplengte-asymmetrie-index, die het staplengteverschil tussen het paretische en niet-paretische been weergeeft, diende als de primaire uitkomstmaat. Secundaire uitkomstmaten omvatten spatiotemporele loopparameters gemeten met de SGAS (d.w.z. stapduur, standduur en de bijhorende asymmetrie-indexen) en loopcapaciteitsmetingen (d.w.z. loopsnelheid en loopbalans). De uitvoerbaarheid werd bepaald door de mate van therapietrouw (het volgen van de trainingssessies) en de tevredenheid over de looptraining. Primaire werkzaamheidsanalyse werd uitgevoerd op basis van ‘intention-to-treat’ met behulp van lineaire gemengde modellen om de behandelingseffecten na de interventie en bij drie maanden follow-up te schatten.

De resultaten van de gerandomiseerde gecontroleerde pilotstudie worden gepresenteerd in *hoofdstuk 7*. De interventieperiode werd voltooid door 19 deelnemers in de experimentele

groep (die MFES-looptraining ontvingen) en 18 deelnemers in de controlegroep (die conventionele looptraining ontvingen). Deze studie bevestigde de uitvoerbaarheid van MFES-looptraining, maar kon geen verschil aantonen tussen MFES-looptraining en conventionele looptraining met betrekking tot de primaire of secundaire uitkomsten. Beide groepen vertoonden vergelijkbare verbeteringen op alle primaire en secundaire uitkomsten. Hoewel beperkt door een kleine steekproefomvang, suggereren de resultaten dat MFES-looptraining uitvoerbaar is, maar dat het waarschijnlijk niet superieur is aan conventionele looptraining om het herstel te bevorderen van spatiotemporele gangsymmetrie, spatiotemporele loopparameters, of loopcapaciteit in een representatieve populatie tijdens vroege revalidatie na een beroerte. Deze conclusie sluit echter mogelijke gunstige effecten van MFES-looptraining niet uit in een meer geselecteerde populatie met een beter potentieel voor het herstel van spatiotemporele loopsymmetrie.

In het laatste hoofdstuk, *hoofdstuk 8*, worden de belangrijkste bevindingen van dit proefschrift besproken en komen enkele methodologische overwegingen aan de orde. De resultaten van de onderzoeken worden in klinisch perspectief geplaatst en aanbevelingen voor toekomstig onderzoek worden gedaan. Ten eerste wordt geconcludeerd dat er verscheidene valide en betrouwbare testen beschikbaar zijn om diverse aspecten van de loopcapaciteit en spatiotemporele loopparameters te meten bij mensen met loopstoornissen na een beroerte. Informatie over meeteigenschappen – responsiviteit, minimaal klinisch relevant verschil en item-responstheoriemodellen – ontbreekt echter en dient te worden onderzocht. Daarnaast wordt aanbevolen om data van een groot aantal schreden te verzamelen om de spatiotemporele loopparameters te evalueren en daarbij een maat voor de gangvariabiliteit toe te voegen. Dit is van belang voor zowel klinisch gebruik als wetenschappelijk onderzoek, aangezien variabiliteitsmaten waardevolle informatie kunnen verschaffen over loopstoornissen en gerelateerde aspecten zoals valrisico, en mogelijk sensitiever is voor verandering dan gemiddelde loopwaarden. Ten tweede lijken de resultaten van de gerandomiseerde gecontroleerde pilotstudie (hoofdstuk 7) in overeenstemming met de literatuur; er is geen superieur effect aangetoond van een trainingsinterventie op het verbeteren van de motorische aansturing van de onderste extremiteit na een beroerte. Deze resultaten pleiten voor het trainen van adaptieve, compensatoire bewegingsstrategieën om de loopcapaciteit te verbeteren in combinatie met medisch-technische interventies (bv. orthesen, focale spasmolyse, en orthopedische chirurgie). Vooralsnog lijkt er onvoldoende bewijs voor het aanbevelen van MFES als onderdeel van de looptraining na een beroerte. Toekomstige studies op het gebied van vroege revalidatie na een beroerte kunnen onderzoeken of een specifieke doelgroep baat kan hebben bij deze behandeling, of elektrische stimulatie van de musculus gastrocnemius tijdens de late standfase van de loopcyclus de afzet van het paretische been kan verbeteren, en of het zelfstandig gebruik van MFES (of als orthese) het herstel bevordert van de loopcapaciteit en de dagelijkse loopactiviteit.

Contributions of authors

Chapter 2. Maijke van Bloemendaal conceived the idea for the study, contributed to the study design and the methodology of the study, collected the articles, contributed to selection of the articles, performed the methodological quality assessment, performed the analysis of the data, and was principally responsible for the drafting of the manuscript. Alexander van de Water contributed to selection of the articles, performed the methodological quality assessment, and assisted in editing the final manuscript. Ingrid van de Port contributed to the study design and the methodology of the study and helped to draft the manuscript. All authors read and approved the final manuscript.

Chapter 3. Maijke van Bloemendaal contributed to the study design and the methodology of the study, collected the data, performed the statistical analysis of the data, and was principally responsible for the drafting of the manuscript. Astrid Kokkeler contributed to the study design and the methodology of the study, collected the data, performed the statistical analysis of the data, and helped to draft the manuscript. Ingrid van de Port conceived the idea for the study, contributed to the study design and the methodology of the study, and was principally responsible for the drafting of the manuscript. All authors read and approved the final manuscript.

Chapter 4. Maijke van Bloemendaal conceived the idea for the study, contributed to the study design and the methodology of the study, performed the statistical analysis of the data, and was principally responsible for the drafting of the manuscript. Walter Bout collected the data and performed data analysis. Sicco Bus contributed to the study design and the methodology of the study and helped to draft the manuscript. Frans Nollet and Alexander Geurts contributed to the study design and the methodology of the study and assisted in editing the final manuscript. Anita Beelen contributed to the study design and the methodology of the study and was principally responsible for the drafting of the manuscript. All authors read and approved the final manuscript.

Chapter 5. Maijke van Bloemendaal conceived the idea for the study, contributed to the study design and the methodology of the study, collected the data, performed the statistical analysis of the data, and was principally responsible for the drafting of the manuscript. Rob Kleissen developed the spatiotemporal gait analysis system and helped to draft the manuscript. Anita Beelen contributed to the study design and the methodology of the study and helped to draft the manuscript. Alexander Geurts and Frans Nollet contributed to the study design and the methodology of the study and assisted in editing the final manuscript. Sicco Bus contributed to the study design and the methodology of the study and was principally responsible for the drafting of the manuscript. All authors read and approved the final manuscript.

Chapter 6. Maijke van Bloemendaal conceived the idea for the study, contributed to the study design and the methodology of the study, and was principally responsible for the drafting of the manuscript. Sicco Bus contributed to the study design and the methodology of the study and helped to draft the manuscript. Charlotte de Boer helped conceive the idea for the study, contributed to the study design and the methodology of the study, and assisted in editing the final manuscript. Frans Nollet and Alexander Geurts contributed to the study design and the methodology of the study and assisted in editing the final manuscript. Anita Beelen conceived the idea for the study, contributed to the study design and the methodology of the study, and was principally responsible for the drafting of the manuscript. All authors read and approved the final manuscript.

Chapter 7. Maijke van Bloemendaal conceived the idea for the study, contributed to the study design and the methodology of the study, collected the data, performed the statistical analysis of the data, and was principally responsible for the drafting of the manuscript. Sicco Bus contributed to the study design and the methodology of the study and helped to draft the manuscript. Frans Nollet and Alexander Geurts contributed to the study design and the methodology of the study and assisted in editing the final manuscript. Anita Beelen conceived the idea for the study, contributed to the study design and the methodology of the study, and was principally responsible for the drafting of the manuscript. All authors read and approved the final manuscript.

About the author

Maijke van Bloemendaal was born on November 22th 1985 in Nijkerk, the Netherlands. In 2004, she graduated from secondary school (Athenaeum, Farel College, Amersfoort). Between 2004 and 2007 she studied Physiotherapy combined with the pre-Master Physiotherapy Science at the University of Applied Sciences Utrecht. During this period, Maijke performed her first research on the clinical assessment of spasticity with the Tardieu Scale in stroke survivors at rehabilitation centre De Vogellanden in Zwolle. After she received her Bachelor's degree (cum laude), Maijke started working as a physiotherapist first for three months at the hospital Isala Clinics in Zwolle and thereafter at the neurological and surgical rehabilitation department at Merem Medical Rehabilitation in Hilversum (formerly known as rehabilitation centre De Trappenberg in Huizen). As physiotherapist, she is particularly interested in the rehabilitation of adults with neurological disorders. Besides her work in the clinic and movement laboratory, she coordinated clinimetrics of the rehabilitation medicine units of Merem for several years. From 2008, she combined her work with the Master Physiotherapy Science (Clinical Health Sciences) at the Utrecht University and in 2010 she graduated cum laude. From August to October 2012, Maijke was involved in developing the masterclass neurorehabilitation of the Master Geriatric Physiotherapy of Avans+ in Breda. Thereafter, she was lecturer Neurology at the Bachelor Physiotherapy of the Amsterdam University of Applied Sciences from November 2012 to January 2013. In 2013, Maijke was given the opportunity – by Merem, in collaboration with the Amsterdam UMC, the University of Amsterdam, and Amsterdam Movement Sciences – to start a PhD project in 2014 which resulted in the current doctoral thesis.

Maijke is married to Bart Vos and they live in Nijkerk with their three daughters, Nora (2013), Marlijn (2015), and Leanne (2018).

Portfolio

Name PhD student: Maijke van Bloemendaal PhD period: January 2014 – December 2021 Name PhD supervisor: Prof. dr. F. Nollet		
1. PhD training		
	Year	**Workload (hours/ECTS)**
General courses		
- BROK ('Basiscursus Regelgeving Klinisch Onderzoek')	2014/2018	34/1.5
- Clinical Data Management	2014	6/0.2
- The AMC World of Science	2014	20/0.7
- Project Management	2014	16/0.6
- Oral Presentation	2015	22/0.8
- Communication with patients	2016	8/0.3
- Didactical Skills	2017	12/0.4
- Scientific writing in English for publication	2019	42/1.5
Specific courses		
- Clinical Epidemiology: Randomized Clinical Trials	2014	16/0.9
- Practical Biostatistics (exam: 7.6)	2015	40/1.1
- Qualitative Health Research	2015	54/1.9
- 'How to write and a publish a study protocol' module by BMJ	2015	5/0.2
- Computing in R	2016	12/0.4
- Entrepreneurship in Health and Life Sciences	2016	42/1.5
- Data analysis in MATLAB	2016	22/0.7
- Clinical Epidemiology: Observational Studies	2016	16/0.6
- Medical literature: Zoeken voor een CAT	2017	2/0.1
- Advanced Topics in Biostatistics	2017/2018	76/2.7
- Pragmatic project management (IMPROVEN)	2019	16/0.6
Presentations		
- Poster presentation on the European Congress on NeuroRehabilitation and Neural Repair, Maastricht (21-22 May 2015)	2015	14/0.5
- Poster presentation and 1-minute pitch on the symposium Kennisnetwerk CVA NL, Eindhoven (25 November 2016)	2016	14/0.5
- Poster presentation and 1-minute pitch at the central stage on the SMALLL congress, Enschede (2 December 2016)	2016	14/0.5
- Poster presentation on the European Congress on NeuroRehabilitation and Neural Repair, Maastricht (23-24 May 2017)	2017	14/0.5
- Poster presentation on the Science Exchange Day, Amsterdam (29 September 2017)	2017	25/0.9
- Poster presentations on the Joint congress of the DCRM, BNF-PRM and RBSPRM 2017 (9-10 November 2017)	2017	14/0.5
- Free paper presentation at the Dutch Congress of Rehabilitation Medicine 2020 (12 November 2020)	2020	14/0.5
- English classic platform presentation at the World Physiotherapy Congress 2021 (9-11 April 2021)	2021	14/0.5
- English presentation at the DCRM across the AMStel meeting of the Amsterdam Movement Sciences (10 May 2021)	2021	14/0.5
Other		
- Symposium Roessingh 'One stop shopping voor loopadvies na CVA: fictie of realiteit' (6 February 2014)	2014	7/0.3
- SMALLL congress (28 November 2014)	2014	7/0.3
- Congress on NeuroRehabilitation and Neural Repair (21-22 May 2015)	2015	14/0.5
- E-learning Joint Commission International - Researchers AMC	2016	2/0.1
- Symposium Sint Maartenskliniek 'Interventies voor loopstoornissen na CVA' (10 June 2016)	2016	7/0.3
- Technology for Health congress (11 October 2016)	2016	7/0.3
- Symposium Kennisnetwerk CVA NL (25 November 2016)	2016	7/0.3
- SMALLL pre-congress and congress (1-2 December 2016)	2016	14/0.5

1. PhD training *(continued)*		
	Year	**Workload (hours/ECTS)**
Other *(continued)*		
- Castor EDC online workshop	2017	2/0.1
- Congress on NeuroRehabilitation and Neural Repair (23-24 May 2017)	2017	14/0.5
- Science Exchange Day (29 September 2017)	2017	5/0.2
- Joint congress of the DCRM, BNF-PRM and RBSPRM 2017 (9-10 November 2017)	2017	14/0.5
- Netwerkbijeenkomst Meer mobiliteit bij neurologische aandoeningen (20 November 2018)	2018	2/0.1
- Dutch Congress of Rehabilitation Medicine 2020 (12-13 November 2020)	2020	14/0.5
- SMALLL congress (3 December 2020)	2020	3/0.1
- World Physiotherapy Congress 2021 (9-11 April 2021)	2021	21/0.8
- DCRM across the AMStel meeting of the Amsterdam Movement Sciences (10 May 2021)	2021	2/0.1

2. Teaching		
	Year	**Workload (hours/ECTS)**
Tutoring/mentoring		
- Student coaching (Geriatric Physical Therapy master thesis)	2015/2016	56/2.0
Supervising		
- Coaching of three students (Bachelor Physical Therapy professional assignment)	2016/2017	56/2.0
- Coaching of a student Movement Technology (internship in the laboratory for body movement analysis)	2016/2017	28/1.0
- Coaching of a student Bachelor Physical Therapy (dissertation)	2017/2018	28/1.0
- Coaching of a student Movement Sciences (internship in the laboratory for body movement analysis)	2019	28/1.0
- Coaching of a student Bachelor Physical Therapy (internship at the neurological and surgical rehabilitation department)	2021	28/1.0

3. Parameters of esteem	
	Year
Awards and prizes	
- Honorable reference at Symposium Kennisnetwerk CVA NL	2016

4. Societal outreach	
	Year
- Speaker in science program 'Kennis van Nu' on television channel NPO2 (14 October 2015)	2015

5. Publications	
	Year
Peer reviewed	
- Gait training assisted by multi-channel functional electrical stimulation early after stroke: study protocol for a randomized controlled trial (Trials 2016, 17:477, DOI 10.1186/s13063-016-1604-x)	2016
- Validity and reproducibility of the Functional Gait Assessment in persons after stroke (Clinical Rehabilitation 2018, 33(1):94-103, DOI 10.1177/0269215518791000)	2018
- Concurrent validity and reliability of a low-cost gait analysis system for assessment of spatiotemporal gait parameters (Journal of Rehabilitation Medicine 2019, 51(6):456-463, DOI 10.2340/16501977-2559)	2019
- Feasibility and preliminary efficacy of gait training assisted by multichannel functional electrical stimulation in early stroke rehabilitation: a pilot randomized controlled trial (Neurorehabilitation and Neural Repair 2021, 35(2):131-144, https://doi.org/10.1177/154596832098194)	2021

List of publications

Peer reviewed international publications

Van Bloemendaal M., Bus S.A., Nollet F., Geurts A.C.H., Beelen A. Feasibility and preliminary efficacy of gait training assisted by multichannel functional electrical stimulation in early stroke rehabilitation: a pilot randomized controlled trial. Neurorehabilitation and Neural Repair. 2021 Feb; 35(2):131-144.

Van Bloemendaal M., Beelen A., Kleissen R.F.M., Geurts A.C.H., Nollet F., Bus S.A. Concurrent validity and reliability of a low-cost gait analysis system for assessment of spatiotemporal gait parameters. Journal of Rehabilitation Medicine. 2019 Jun; 51(6):456-463.

Van Bloemendaal M., Bout W., Bus S.A., Nollet F., Geurts A.C.H., Beelen A. Validity and reproducibility of the Functional Gait Assessment in persons after stroke. Clinical Rehabilitation. 2019 Jan; 33(1):94-103.

Van Bloemendaal M., Bus S.A., De Boer C.E., Nollet F., Geurts A.C.H., Beelen A. Gait training assisted by multi-channel functional electrical stimulation early after stroke: study protocol for a randomized controlled trial. Trials. 2016 Oct; 17(1):477.

Van Bloemendaal M., Van de Water A.T.M., Van de Port I.G.L. Walking tests for stroke survivors: a systematic review of their measurement properties. Disability and Rehabilitation. 2012 Dec; 34(26):2207-2221.

Van Bloemendaal M., Kokkeler A.M., Van de Port I.G. The shuttle walk test: a new approach to functional walking capacity measurements for patients after stroke? Archives of Physical Medicine and Rehabilitation. 2012 Jan; 93(1):163-166.

National publications

Van Bloemendaal M., Egdom A.M. Groepsbehandeling op maat voor de bovenste extremiteit na beroerte. FysioPraxis. 2013 Aug; 22(8):44-46.

Barten D., **Van Bloemendaal M.**, Van Dijk S., et al. Functionele bekostiging: kansen en bedreigingen voor de fysiotherapie. FysioPraxis. 2010 Aug; 33.

Book chapters

De Jong L.D., **Van Bloemendaal M.** Contracturen in de afunctionele arm na een CVA: preventie en behandeling in de revalidatiefase. Hoofdstuk 4, Jaarboek Fysiotherapie Kinesitherapie 2010. Bohn Stafleu van Loghum. 2010; 66-78. ISBN 978 90 313 64756.

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Amsterdam Movement Sciences

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Amsterdam Movement Sciences conducts scientific research to optimize physical performance in health and disease based on a fundamental understanding of human movement in order to contribute to the fulfillment of a meaningful life.