Advances in the assessment and rehabilitation of ambulatory chronic stroke survivors

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By

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Abstract

Walking at a functional level is a requirement for walking safely in the community. Walking at a functional level requires good balance control and the ability to perform functional tasks while walking in challenging situations such as walking across a busy road. This thesis attempts to answer a number of questions regarding assessment of walking at a functional level in older people at risk of falls and in stroke survivors. The first part of the work involves a systematic review.

The aim of the systematic review is to identify the available clinical OM used in clinical physiotherapy to assess walking at a functional level for stroke rehabilitation and to evaluate their psychometric properties. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines. The Consensus-based Standards for the selection of health status Measurement Instruments (COSMIN) tool was used to assess the risk of bias in the quality of the methodological design and statistical methods in reliability, validity, and responsiveness in the included studies. Fifty-four studies were included in the review, six OM were identified for dynamic balance, twenty-one OM for functional gait, and three studies including five tests each for motor and cognitive tests to assess dual task while walking. The most tested psychometric properties were reliability and construct validity. Studies on responsiveness were limited.

The aim of the first experimental study (Chapter 5) is to identify the associations between walking at a functional level and subjective visual verticality (SVV), cognitive function, psychosocial aspects, and physical activity (PA) levels. Twenty chronic stroke survivors capable of independently walking at least 6 metres and twenty healthy controls were recruited in this study. Assessment of functional-level walking included the Mini-Balance Evaluation Test (Mini-BESTest), and the Functional Gait Assessment (FGA). The Rod and Disc test was used to assess the SVV, the Cambridge Neuropsychological Test Automated Battery (CANTAB) tests for the cognitive functions, a set of questionnaires were used to assess psychosocial aspects and the AX3 monitor to determine the PA levels. The difference was significant between the groups in the Mini-BESTest and the FGA ($p<0.001$), lower (i.e., worse) Mini-BESTest and FGA scores were observed for ambulatory chronic stroke survivors. Balance confidence emerged as a key factor associated with both the Mini-BESTest and the FGA in ambulatory chronic stroke survivors. The Spearman's rank-order correlations between the balance confidence scale and the Mini-Best, and the FGA were (r_s = 0.72 and 0.75) respectively in ambulatory chronic stroke survivors. The results suggest that there is a need for rehabilitation for walking at a functional level for ambulatory stroke survivors and balance confidence should be considered in their assessment and treatment.

Difficulties in balance control and limited walking functions are also common in older adults and increase their risk of falls. Both populations (older adults at risk of falls and stroke survivors) need balance training rehabilitation based on a multifactorial approach, which current rehabilitation programmes do not incorporate. Current rehabilitation programmes are limited to simple physical exercises. In addition, previous studies have shown that adherence rates to exercise rehabilitation programmes are low. Using telerehabilitation can enhance adherence rates and adds enjoyment to the exercise rehabilitation programmes.

The aim of the next experimental work presented in this thesis was to assess the feasibility and acceptability of a novel telerehabilitation system in older adults at risk of falls and ambulatory chronic stroke survivors: the HOLOBalance system. This is a platform that uses a hologram to deliver the exercise instructions for balance training and uses wearable sensors to detect simultaneous body movements. The training addresses all components relevant to balance using multisensory rehabilitation exercises, exergames, and cognitive training. In addition to assessment of feasibility and acceptability, trends of improvement in balance and functional gait were also investigated. This was undertaken in both older adults at risk of falls and stroke survivors. For older adults at risk of falls (n=54) the participants were randomised to HOLOBalance intervention home-based (HOLOBalance), clinic based (HOLOBox) or control groups. In a second study, the HOLOBalance system (clinic based HOLOBox) was assessed for feasibility and acceptability in stroke survivors (n=8).

The main finding from both feasibility studies was that the HOLOBalance system was feasible and acceptable for older adults at risk of falls and ambulatory stroke survivors, as assessed by drop-out, adherence rates, exit interviews, and usability scales. The preliminary data showed that there were trends of improvement in balance and functional gait measures in the intervention groups (HOLOBalance and HOLOBox) in the older adults, and in the stroke survivors who had received the clinic based HOLOBox intervention.

Declaration

I hereby declare that this thesis represents my own work which has been done after registration for the degree of PhD at King's College London and has not been previously included in a thesis or dissertation submitted to this or any other institution.

All human research was conducted after obtaining ethical approval from King's College London (Chapter 5, 6, and 7).

The HOLOBalance study was funded by the European Union Horizon 2020 research and innovation programme under grant agreement 769574. The HOLOBalance has been developed by the HOLOBalance team to create a new balance training environment. HOLOBalance is a multicentre research based in Athens, Freiburg, and London. I was engaged in the HOLOBalance system setup and offered the treatment sessions and follow-up for all participants in all groups for older adults at risk of falls for the study group at London. Chapter 6 presents the HOLOBalance system feasibility for older adults at risk of falls, data from other research centres in Athens and Freiburg were included in the analysis of the secondary outcomes. The feasibility of the HOLOBalance system for stroke survivors was also investigated by myself and findings are presented in Chapter 7.

Impact of COVID-19 restrictions

All studies in the thesis were run during the COVID-19 pandemic. The COVID-19 pandemic has affected research specially during the lockdown period. A variety of restrictions were in place and limited the progress in research, especially for data collection when face-to-face meetings were restricted. As institutions had limited in-person activities for safety precautions, research was significantly disrupted and created barriers, such as limiting sample size.

Acknowledgements

I would like to extend my heartfelt appreciation and acknowledgement to my supervisors, Doctor Marousa Pavlou, Professor Stephen Harridge, and Doctor Isaac Sorinola for their invaluable guidance and support throughout the entire process of completing my thesis.

Words cannot express my gratitude to my supervisors, their expertise, patience, and dedication have been instrumental in supervising my research and ensuring its quality. They have consistently provided valuable insights, constructive feedback, and encouragement, which have greatly enhanced the overall quality of my work. I am grateful for their endless support, timely guidance, and their commitment to helping to succeed.

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Thanks, should also go to the study participants for their volunteering and willing to participate, especially during the difficult time COVID-19 pandemic.

I would like to extend my sincere thanks to my scholarship funder King Saud University and the Saudi Cultural Bureau in London.

Lastly, I would be remiss in not mentioning my family, especially my parents, spouse, and daughters. Their belief in me has kept my spirits and motivation high during this process.

Table of Contents

Table of Tables

Table of Figures

Abbreviations

AR	Augmented reality
AUC	Area Under the receiver operating Curve
β	Beta level
BBC	Berg Balance Scale
BEST test	Balance Evaluation System Test
CB&M scale	Community Balance and Mobility scale
CANTAB	Cambridge Neuropsychological Test Automated Battery
CCW	Counter-clockwise
COSMIN	Consensus-based Standards for the selection of health status Measurement Instruments
COVID	Coronavirus Disease (SARS-CoV-2)
CW	Clockwise
DGI	Dynamic Gait Index
DT	Dual Task
EQ-5D-5L	European Quality of life-5 Dimension
FGA	Functional Gait Assessment
ICC	Intra-class Correlation Coefficient
IMU	Inertial Measurement Unit
KCL	King's College London
MD	Methodological Design
MDC	Minimum Detectable Change
MET	Metabolic Equivalent of Task
MIC	Minimum Important Change
Mini-BESTest	Mini- Balance Evaluation System Test
MoCA	Montreal Cognitive Assessment
MSR	Multi-sensory Rehabilitation
n	Sample size
OM/OMs	Outcome Measures
p	p-value or probability value
PASIPD	The Physical Activity Scale for Individuals with Physical Disabilities
PPA	Physiological Profile Approach test
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
r	Pearson's correlation
r_s	Spearman's correlation
SD	Standard Deviation
SEM	Standard Error of Measurement
SM	Statistical Method
SVV	Subjective Visual Verticality
TUG test	Timed Up and Go test
VO2	Volume of Oxygen uptake
VR	Virtual Reality
UK	United Kingdom

x̄	Mean
10mWT	10 metres walk test
6MWT	6-Minute walk test

Glossary

Centre of gravity: centre of gravity of the human body is a hypothetical point around which the force of gravity appears to act. It is a point at which the combined mass of the body appears to be concentrated (1).

Centre of mass: the distribution of mass is even around the point of centre of mass, and it is where the body's relative position is determined to be zero (2).

Disability: is limitations in multiple functional life areas. It is seen as a result of an interaction between a person (with a health condition) and that person's contextual factors (environmental factors and personal factors). Disability covers a spectrum of various levels of functioning at body level, person level and societal level (3).

Dynamic balance: is the ability to remain stable while performing movements or actions that require displacing or moving oneself (4).

Haemorrhagic stroke: it is a type of stroke which occurs due to the rupture of a blood vessel and results in intracerebral bleeding and/or subarachnoid haemorrhage (5).

Impairment: is a problem in body function and/or structure such as significant deviation or loss (3).

Ischemic stroke: is a type of stroke which occurs due to a loss of blood supply to an area of the brain resulting in cerebral or cerebellar lesions (5).

Metabolic Equivalent of Task (MET): is the objective measure of the rate at which a person expends energy, and classified to sedentary < 1.5 MET, light < 3 MET, moderate > 3 MET< 6 MET, vigorous > 6 MET (6).

Psychometric properties: are the characteristics and qualities of tests used for assessment that determine their reliability, and validity. These properties help ensure that the measurements are accurate and meaningful (7).

Reliability: is related to stability of scores from an outcome measure in repeated measurement (i.e., under several conditions) from a patient who is stable and has no change in health condition. The main types of reliability are: the test-retest reliability where the time is varied; the intra-rater reliability where the occasion is varied; and in the inter-rater reliability, the rater (assessor) is varied between measurements (8,9).

Responsiveness: is the ability of a measurement to detect change over time, or between subgroups in the construct to be measured (10).

Sensory reweighting: is the ability to adapt between sensory input from visual cues, vestibular system and proprioception according to environmental and task demands for balance control (11,12).

Static balance: is the ability to maintain balance control in sitting, standing, or shifting the weight in standing (4).

Stroke: is a rapidly developing clinical sign of focal or global disturbance of cerebral function, with symptoms lasting 24 hours or longer with no apparent cause other than vascular lesion" (5).

Subjective Visual Verticality: is the perception of verticality, which is a multi-sensory mediated sense that allows human beings to accurately ascertain what is up and what is down and therefore deviations in a gravitational field (13).

Telerehabilitation: is an intervention to improve a particular functioning of individuals using technologies and telecommunication to provide activities and monitor progress and safety from a distance (14).

Walking at a functional level: is the ability to perform functions while walking which can be as simple as turning one's head while walking or as complex as walking to cross a busy road. Walking at a functional level also involves carry a secondary motor or cognitive task while walking which is known as dual task walking (15,16).

Visual dependency: is a reduced ability to disregard visual cues in complex or conflicting visual environments (e.g., height, crowd, or traffic) which leads to an over-reliance on vision for balance control (17).

Validity: is the degree to which an instrument measures the construct it intends to measure; it consists of a) face validity which reflects whether the measure is acceptable to measure the context from the practitioners' view; b) content validity, which is the degree to which the content adequately reflects the construct to be measured; c) criterion validity, which is the degree to which the scores of an instrument are an adequate reflection of a 'gold standard' measure; d) structural validity, which reflects the dimensionality of an instrument to evaluate the required aspects of measurement; e) construct validity, which reflects the degree to which the score of a measurement is consistent with hypotheses for another measurement with a similar concept (convergent validity) or opposite concept (divergent validity); and f) known group validity, which is differentiation between subgroups (such as fallers and non-fallers) (10,18).

Chapter 1: Introduction

Strokes are the third most common cause of morbidity and mortality and the second-leading cause of death globally (19). Stroke incidence increased by 15% and prevalence by 22% in people aged under 70 in 2019 compared to 1990 (20). In the UK, approximately 1.3 million people are living with stroke, and the incidence rate is 100,000 strokes every year (21), and the current annual societal cost is about £25.6 billion (22). The World Health Organisation (WHO) defines stroke as "rapidly developing clinical signs of focal or global disturbance of cerebral function, with symptoms lasting 24 hours or longer or leading to death with no apparent cause other than vascular lesion" (5). Stroke or cerebrovascular accident (CVA) is caused by reductions in blood flow to the brain of sufficient duration and extent to lead to damage of neuronal networks, with subsequent damage in sensation, movement, and/or cognition (23).

Stroke can be either ischemic or haemorrhagic. Ischemic stroke is a common type of stroke, caused by the loss of blood supply to an area of the brain resulting in cerebral or cerebellar lesions. Heamorrhagic stroke occurs due to the rupture of a blood vessel and results in intracerebral bleeding and/or subarachnoid haemorrhage (24). In either stroke type, the risk of developing stroke increases with risk factors such as hypertension, smoking, diet, and physical inactivity, also with age, sex, and race/ethnicity.

Recently, inflammatory disorders, infection, pollution, cardiac atrial disorders, and atrial fibrillation have been identified as factors which can trigger stroke (25). In addition, genetic disorders may play a role in increasing the risk of stroke (26,27). For example, studies have shown that the following genetic disorder diseases were associated with stroke: Fabry disease, which involves vertebrobasilar circulation, dolichoectasia (i.e., elongated) of cerebral vessels, and white matter abnormalities in the brain; sickle cell disease; and moyamoya, which is a stenosis and occlusion of the bilateral distal internal carotid arteries and proximal middle/anterior cerebral arteries (28).

In addition to all the risk factors mentioned earlier, recent studies have shown that there is a relationship between Coronavirus disease 2019 (COVID-19) and acute stroke (29). A meta-analysis found that among 108,571 patients with COVID-19, acute stroke occurred in 1.4% (95%CI) (29). Stroke in COVID-19 patients was ischemic (30), while patients who had stroke after severe COVID-19 infection were younger (<60 years) and needed longer hospitalisation compared to stroke survivors with no COVID-19 infection (29).

In the last decade, the quality of acute care for stroke survivors has been improved (31). For example, acute ischemic stroke patients can receive intravenous thrombolysis and intra-arterial thrombectomy to promote oxygenated blood flow in the ischemic tissue (32,33). This helps in reducing the chances of prolonged hospital time and the manifestation of severe disability (34). However, limitations in physical and other abilities require prolonged rehabilitation to return to functional life (35). One-third of stroke survivors experience significant residual disability impacting their quality of life (36). Stroke in younger adults can also be more burdensome and have higher mental and psychosocial consequences (30) with high rates of mortality (37).

Mobility problems are among the most frequent and disabling effects of stroke (38). Mobility problems arise due to muscle weaknesses, spasticity, impaired coordination, and decreased joint range of motion. These impairments increase the challenge for stroke survivors to move independently, perform daily activities, and maintain their balance (39). Balance control is a multifactorial process which depends on generating the appropriate pattern of muscle contractions required to organise postural tone in relation to different environments (40,41). Balance dysfunction is a distressing problem for stroke survivors with 83% of stroke survivors experiencing it (42). It affects their daily life and activities (43), and is associated with a high risk of falls (44–48).

Identifying the best treatments to improve balance, mobility, and walking were among the top ten research priorities relating to life after stroke by the James Lind Alliance Priority Setting Partnership for Stroke (49). Treatment goals for balance rehabilitation should target all balance components and be individualised for each case (38), however, it is unclear what are the factors associated with balance for ambulatory stroke survivors. Identifying these factors can help in goal setting and providing more individualised treatment.

In addition to the importance of goal setting for optimal stroke rehabilitation, there is a need for highly accurate assessment to address certain needs (7). Although balance assessment for stroke rehabilitation was reviewed by Pollock et al (2011) and Bambirra et al (2015) (50,51), the focus was on balance from sitting or standing and not for dynamic balance such as while walking. Therefore, there is a need to systematically review and appraise the available outcome measures (OM) according to their psychometric properties used for balance assessment for ambulatory stroke survivors.

Despite rehabilitation after a stroke including exercises for balance control and the fact that stroke survivors may improve and be able to walk independently after stroke (52,53), there is much evidence stating the return to optimal function levels such as walking in the community and improving physical activity (PA) are challenging (54–57). Identifying the factors which are linked to walking at a functional level in stroke survivors in comparison to healthy controls could help in addressing individualised goal setting and treatment plans for ambulatory stroke survivors.

Balance dysfunction is also common in older adults (47,58), because older adults are at risk of developing sarcopenia (weakness of skeletal muscles), which, in turn, increases the risk of fragility (59–61). In addition, vestibular dysfunction is common with the ageing process (48,62). These factors lead to difficulties in balance control, especially in challenging situations, which increases the risk of falls in older adults (63–65).

Meanwhile, telerehabilitation has shown positive results and is a growing field in physiotherapy treatment for long-term conditions (66–69). Telerehabilitation is a virtual form of rehabilitation that involves the use of telecommunication technology to provide remote rehabilitation services, such as video conferencing with healthcare professionals, interactive online exercises, and monitoring of progress (66,70,71). Some benefits of telerehabilitation include easy access to rehabilitation services from the comfort of one's own homes, and reducing the need for travel, which is particularly beneficial for patients living in remote areas or with limited mobility. In addition, healthcare professionals can remotely monitor patients' progress, and provide feedback (66,70,71). Furthermore, telerehabilitation provided a safe environment during the COVID-19 pandemic to reduce the risk of exposure to infections for vulnerable populations (29,70,72).

One innovative telerehabilitation system — the HOLOBalance system —uses holograms to help with the provision and practise of balance training. There is a need to assess the feasibility and acceptability of this system in older adults at risk of falls, and if it is feasible, it could be assessed for stroke survivors.

The aims of the work presented in this thesis are firstly to undertake a systematic review to identify the outcome measures used to assess walking at a functional level in stroke rehabilitation and evaluate their psychometric properties. It will then identify the factors associated with walking at a functional level for ambulatory stroke survivors in comparison to healthy controls; and finally, it aims to determine the feasibility and acceptability of a new telerehabilitation system — HOLOBalance system — for balance training in both older adults at risk of falls and ambulatory stroke survivors.

Chapter 2: Literature Review

The purpose of this chapter is to provide a background for the importance of balance control in older adults at risk of falls and stroke survivors. The following sections will summarise the mechanisms of balance control, and the anatomical and physiological components of balance control. It will also include a background of the fundamental changes associated with the ageing process and after stroke. This is put in the context of how these are integrated for walking. In addition, this chapter will provide an overview of the assessment and treatment strategies for balance control and walking at the functional level.

2.1 The mechanism of balance control

Balance problems are common and can result in major injuries and falls in older adults (73). Falls may lead to complex injury, hospitalisation, and increased healthcare costs (63). In a study by Melzer et al (2010), among ninety-nine adults aged 65-91 years, with a mean age of 78.4 (SD 5.7), 29 subjects reported at least one fall in the past 6 months (74). In stroke survivors, the fall incidence is high, with up to 70% having experienced a fall (75). In this population, falls have been associated with impaired balance (45) and a more limited functional status (76). A recent systematic review of 27 studies by Abdollahi et al (2022) showed that among stroke survivors increased fall risks were associated with a group of factors (77). Although these factors include age in 38%, cognitive impairment in 36%, and gender in 24% of stroke survivors (77), but more importantly factors such as limitations in movement in 84%, poor balance in 81%, and limited motor function in 65% showed higher percentages of increased fall risks in stroke survivors (77).

Balance control is an essential component when performing functional tasks while walking and participating in physical activity (PA) (78,79). Balance control is defined as "the ability to maintain the centre of gravity within the base of support" (4). It is a multifactorial process that relies on the integration of sensory systems (vision, vestibular and proprioception), musculoskeletal components (including muscles, bones, and joints), neuromuscular synergies, adaptive and anticipatory mechanisms as well as cognitive function (41,80). Figure 2-1 illustrates the mechanisms involved in the control of balance (81). Regulation between balance components is continuously monitored by the central nervous system (CNS) to allow compensation of internal and external perturbations during a variety of body positions and motions such as walking (41,79). More specifically, sensory inputs from visual cues, and the vestibular and somatosensory systems are processed within the CNS to support appropriate balance control through anticipatory postural adjustments (i.e., preparation for movement) and adaptation according to environmental and balance demands (80,82). The following paragraphs expand on the factors associated with postural control after perturbation and the sensory inputs for balance control.

Balance control requires postural orientation and postural equilibrium. The former involves aligning the trunk and head with gravity, support surfaces, and the visual surroundings, while the latter involves coordination of movement strategies to stabilise the body during disturbances (83). Cognitive processing for balance control depends on task complexity and integration of control systems (83). In addition to static balance control, control balance in dynamic conditions (i.e., dynamic balance control) is essential for catching and avoiding falling, which is achieved through feed shifts in stable body equilibrium. This involves relocation of the relevant body configuration, where multiple muscles are activated and the hierarchy between reciprocal and co-activation of agonist and antagonist muscles is crucial (84).

In the presence of perturbations, extra muscle synergy with complementary function needs to be created to increase the robustness of motor output and therefore to cope with perturbation for dynamic balance control (85). These perturbations can be in an anterior-posterior directions or in mediolateral directions. A recent study by Rizzato et al (2023) investigated the neuromuscular control mechanisms involved in underpinning static and dynamic postural tasks by investigating changes in the centre of pressure trajectory over a force platform in anterior-posterior and medio-lateral directions for 15 healthy subjects. The results showed that the dynamic tasks included smaller intervals of critical points which determine the limit of balance control in mediolateral directions compared to anterior posterior directions with more closed-loop corrective feedback mechanisms (86).

A further study by Porter et al (2015) tested the centre of pressure displacement and velocity in the anterior-posterior and medio-lateral directions while standing quietly for 30 seconds, walking and then taking a lateral step and standing quietly in 16 older adults (60–90 years) compared to 14 young adults (20–40 years). The results of this study showed that older adults displayed a larger centre of pressure velocity up to thirty seconds after taking a lateral step in the medio-lateral direction (87), and this delay would increase risk of falling.

Furthermore, changes in multisensory inputs provoke immediate changes in posture, corresponding to available sensory input. These immediate alterations occur when the brain predicts sensory inputs and corrects the body's motion based on a discrepancy between the predicted and actual sensory inputs. These multisensory inputs (vision, vestibular, proprioception and exteroception) are then integrated to represent the body state to generate motion (88). Horak et al (1990) developed the “weight and reweight” concept to understand the multisensory integration to calculate body state, including parameters such as the centre of gravity and heading (62) (Figure 2-2). Sensory inputs include signal noise, and the multisensory “integrator” decides which inputs are reliable, and to what degree, as a “weighting” process (88). The CNS then reweights (changes the weights) the inputs according to the internal and external conditions of the body and surrounding to sustain balance control and prevent falls (62,88). However, the mechanisms can be altered due to sensory loss such as in people with vestibular dysfunction (62).

The ability to adapt between sensory inputs according to environmental and task demands is essential and known as sensory re-weighting (11,12,89–91). Deficits in sensory reweighting can result in an over reliance on visual cues (11,12,89–91), and impact balance control (92). This can result in visual dependency and can affect the perception of verticality and has also been found to increase with age (89,90). Accurate perception of visual verticality is important for maintaining an upright posture and for walking since the role of visual fields was shown to be predominant for upright maintenance (93).

People with visual dependency report symptoms such as dizziness, disorientation and postural and/or gait instability, which is provoked or exacerbated in environments with busy or conflicting visual motion including crowds, such as supermarkets and scrolling computer screens (17,94,95). The perception of Subjective Visual Verticality (SVV) has been shown to be a consequence of lesions involving the central vestibular pathways (brainstem, thalamus, or cortex) on either side (96). Furthermore, studies have shown that visual dependency is a main contributor to balance problems in peripheral vestibular disorders (17,95) and in acute stroke survivors (11,12,89–91).

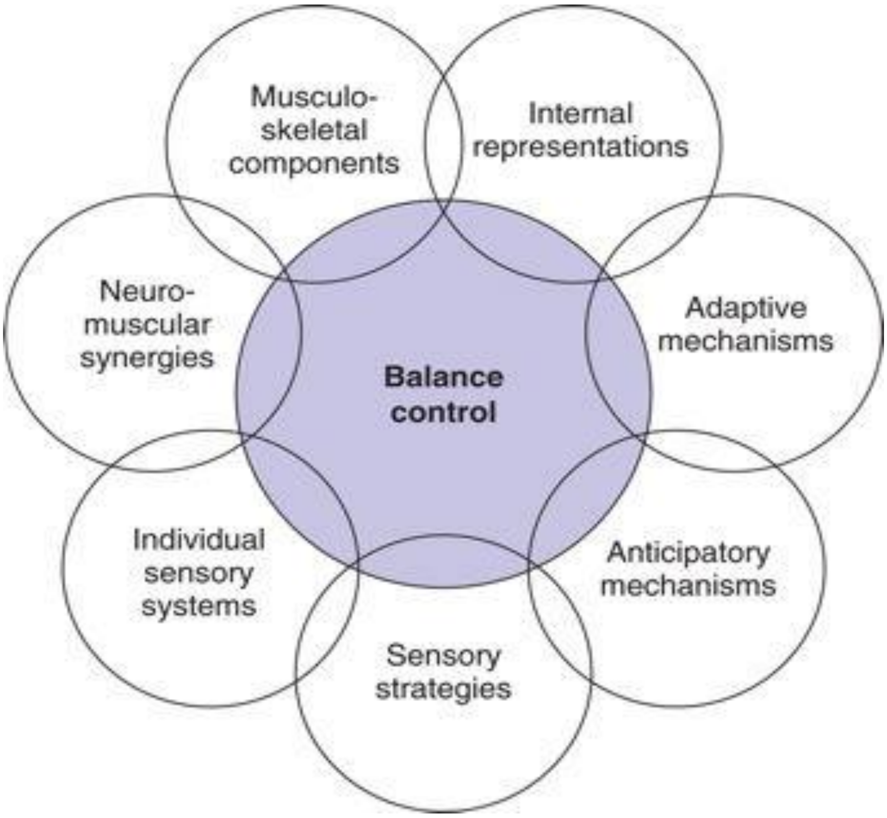


Figure 2—1 The integration between the balance control components (41).

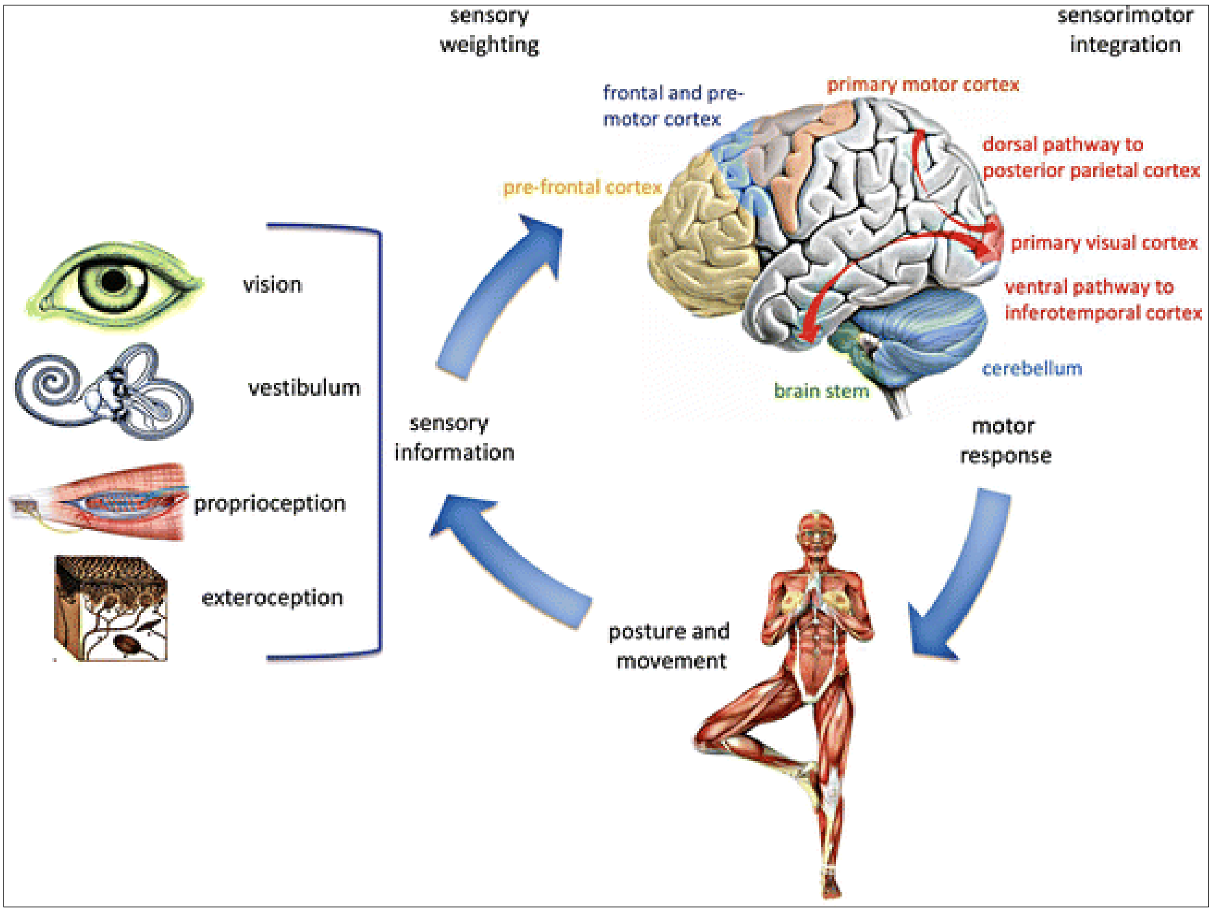


Figure 2—2 Sensory information, sensory weighting sensory-motor integration for balance control (81).

2.2 Anatomical structures and physiological functions

2.2.1 Vestibular system

Balance control and the orientation of the body in relation to the environment require the vestibular centres in the brainstem, cerebellum, and cerebral cortex function to integrate sensory information from the peripheral vestibular organs, visual system, and proprioceptive system. This section provides a brief background of the anatomical and mechanical processes of the vestibular system.

The peripheral vestibular system located in the inner ear, includes the utricle, saccule, lateral, superior, and the posterior semicircular canals. Meanwhile, the central vestibular system consists of parts starting from the brainstem to the cerebellum, formatio reticularis, thalamus, and vestibular cortex (97), presented in Figure 2-3. Hair cells on the neuroepithelium of the peripheral vestibular organs carry sensory impulses to primary processing centres in the brainstem and the cerebellum. These areas send inputs via ascending and descending projections to coordinate vital reflexes, such as the vestibulo-ocular reflex and the vestibulospinal reflex for the proper orientation of the eyes and body in response to head motion (98,99).

There are massive afferent and efferent cellular connections in the vestibular system in the inner ear and within the petrous temporal bone which includes a bony labyrinth and a membranous labyrinth which is filled with a perilymph fluid. This fluid is high in potassium ion concentration which is produced by the Vestibular Dark Cells. Meanwhile, the sensory neuroepithelium in the utricle, saccule and the semicircular ducts is the crista ampullaris.

Neuroepithelial structures contain specialised mechanoreceptor cells called "hair cells" which contain a vast number of cross-linked actin filaments called stereocilia (100,101).

Acceleration of endolymph results in the movement of stereocilia, leading to either depolarization or hyperpolarization depending on the direction of head movement. For example, movement towards the kinocilium causes the interconnected tip links to pull open cation channels resulting in an influx of potassium ions and depolarization. In turn, the depolarized hair cell releases glutamate to afferent nerve receptors and results in neurotransmission to the vestibular ganglion. Movement in the opposite direction to the kinocilium causes stereocilia to converge, resulting in tip links closing the cation channels. Meanwhile, a lack of potassium influx causes hyperpolarization of the hair cell and inhibition of glutamate release to the afferent nerve (100,101).

Afferent nerve signals carried by the vestibulocochlear nerve are interpreted by the central vestibular system, presented in Figure 2-4. The central vestibular system unites the peripheral signals from both ascending pathways to elicit eye, head, and body motor responses for the control of balance and orientation (100,101). Dysfunction in the vestibular system can manifest symptomatically as vertigo, nausea, vomiting, visual disturbance, hearing changes, and various cognitive deficits including impairment of spatial navigation, learning, and object recognition (100).

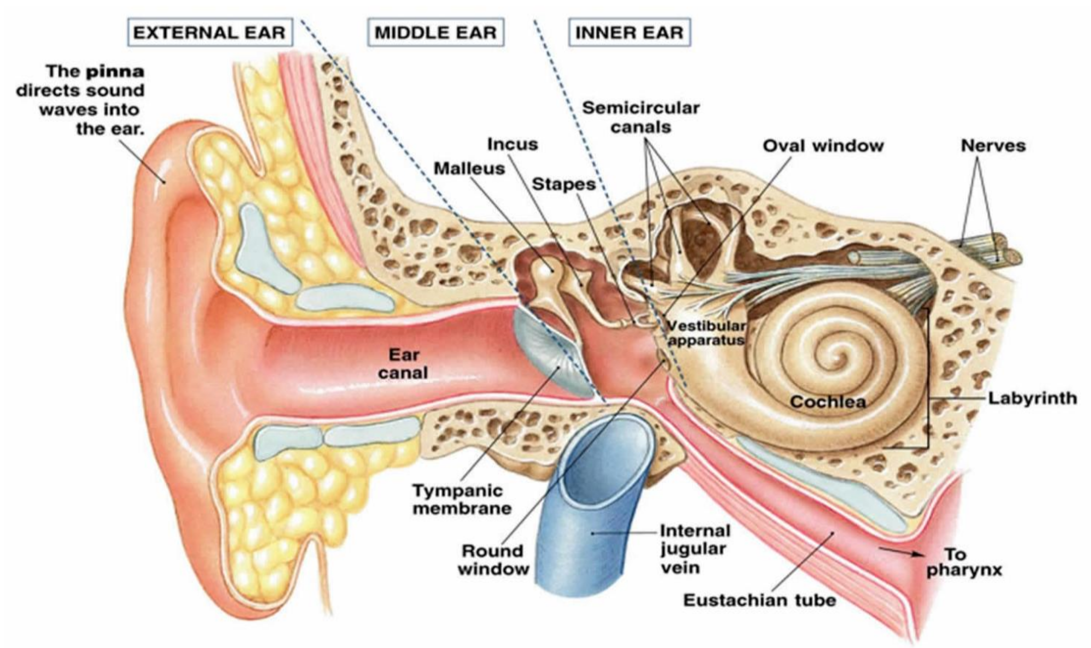


Figure 2—3 Anatomical structure of the peripheral vestibular system (99).

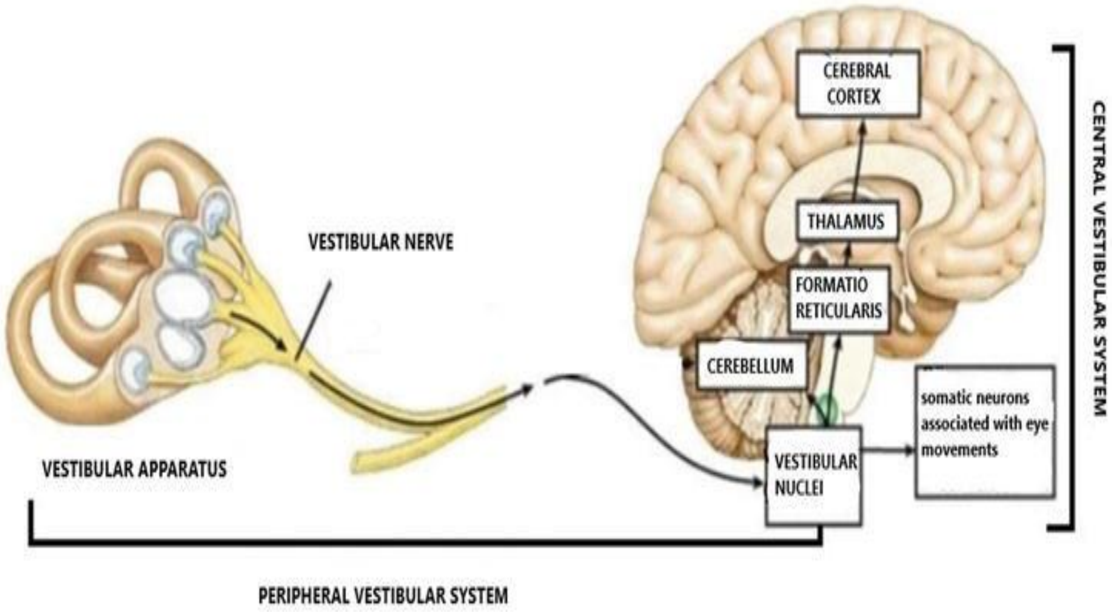


Figure 2—4 The vestibular nerve and the central vestibular system (97).

2.2.2 Proprioception and mechanoreceptors

Proprioception is the internal sense of body position, and proprioceptive control of locomotion is essential to generating and maintaining precise patterns of movement. The degradation of proprioception results in the loss of acuity in movement control, which is worsened by the deprivation of complementary sensory modality, and poor motor learning (102).

Proprioceptive inputs modulate inter-neuronal pools and help provide dimensional information for motor control (103) and joint stability (104). Proprioceptors are neurons located within skeletal muscles and tendons (i.e., muscle spindles), and joints (i.e., mechanoreceptors). These muscle spindles are made of capsules from connective tissue that contain specialised intrafusal muscle fibres positioned in parallel with the extrafusal muscle fibres. The projections of primary sensory neurons (i.e., afferents) spiral around the central portion of intrafusal fibres (muscle spindles). These are supplied by motor neurons and respond to muscle stretch with brief bursts of action potentials (105).

Mechanoreceptors are sensitive to mechanical stimuli and transmit information on the position and motion of the joints to the CNS (106). These mechanoreceptors are important for functional joint stability and dynamic activity and take into account the current and changing positions of the joints before and during a motor command, to account for the complex mechanical interactions within the components of the musculoskeletal system (107). Additionally, tactile feedback from the skin provides information about body conformation and skin deformation during movement, and points of skin contact with an object also provide proprioceptive information (105).

A study by Hazime et al (2012) of 11 healthy subjects, found increased centre of pressure speed during proprioception perturbation independently of the vision condition during double leg standing whereas in single leg stance, visual input was more important since there was an increased centre of pressure speed during reduced vision condition (108). The vision perturbation procedure was achieved by using a darkened room and keep a red spot in front of the subjects to focus on (108). A further experiment by Bagesteiro et al (2006) focused on addressing the relative contributions of vision and proprioception to specification of movement distance in a Virtual Reality (VR) environment - which provides a virtual environment for the patient and involves the use of interactive exercise-based video games - for 8 healthy subjects. The study found that movement distance was modified according to the virtual start location.

Meanwhile, Bagesteiro et al (2006) found that visual information is important in starting the location to determine the initial peak in tangential hand acceleration, while proprioceptive information determine the duration of initial acceleration (109). There is a need of further investigation for understanding the interaction between sensory information for patients with somatosensory impairments, because this can help in providing different therapeutic exercises.

2.3 Common physiological changes associated with the ageing process and balance control

2.3.1 Changes in peripheral vestibular organs associated with ageing

Vestibular dysfunction is common in older adults (48,58,110). A study of 740 individuals over the age of 65 screened for otologic evaluation found that 21% of the individuals had identifiable causes of dizziness and 79% had progressive disequilibrium of ageing in which pathological changes other than those in the peripheral vestibular system seem to be responsible for disequilibrium of ageing (111). Changes in the peripheral vestibular system in the ageing process include a progressive degeneration and/or loss of hair cells in both the otolith organs and semicircular canals, and Scarpa's ganglion neuronal degeneration (112,113). In addition, alterations in calcium metabolism and microvascular ischemia, which may all play a role in vestibular decline associated with ageing, were found (114).

Since the vestibular system plays an essential role in maintaining balance (98), the decline in vestibular function with ageing is associated with deficits in gait, unsteadiness, increased risk of falls, and impairments in emotional functioning (110,115). In particular, the loss of horizontal semicircular canal function has been linked to slower gait speed (116). A survey by the National Health and Nutrition Examination Surveys from the National Centre for Health Statistics indicates a high prevalence of difficulties with vestibular function among the elderly, with 69% of those aged 70–79 and 85% of those aged 80+ having vestibular dysfunction (117); and a strong association between vestibular dysfunction and increased risk of falls has been found (117). Moreover, a study comparing age-matched fallers and non-fallers, found that the prevalence of elderly adults with a clinically significant vestibular impairment who fell was much larger (80%), compared to those who did not (19%) (48).

Decline in vestibular function and poor balance control are related to impairments in emotional functioning (17). Fear of falling and safety concerns are the most distressing problems, leading to anxiety (18), and potentially to decreased socialisation, which is an important outcome (19). Addressing the problems in balance in relation to vestibular dysfunction is important not only for physical independence, but also for healthy emotional and social functioning.

2.3.2 Hearing disturbance associated with ageing

A review by Walling et al (2012) showed that hearing disturbance affects approximately one-third of adults aged 61 to 70 and more than 80 percent of those older than 85 (118). The most common type is conduction of sound vibrations to the inner ear and the conversion to electrical impulses for conduction to the brain (118). Hearing loss has a significant impact on communication and interactions (119), and is also associated with isolation (120). In addition, hearing loss may affect gait - one study found that for 49% of participants, with a mean age of 76.5 years, (auditory acuity was measured using a pure tone average of hearing thresholds for 0.5-4 kHz tones in the better-hearing ear), and showed that poor pure tone average was associated with slower gait speed and stride length variability (121).

2.3.3 Changes in proprioception associated with ageing

Several studies have identified that there is a negative association between ageing and decreased proprioception function (122). Studies have shown that the proprioception decline in the lower limbs is associated with problems of balance in older age who had experienced falls (106,123,124). One study of 166 participants classified into 3 groups - younger (60–69 years, n = 56), middle (70–79 years, n= 57), or older (≥80 years, n= 53) aged groups - reported significant differences among the three groups in the Berg Balance Scale (BBS) scores ($p < 0.001$), tactile sensation at the big toe ($p = 0.015$) and heel ($p = 0.025$), proprioception of knee flexion ($p < 0.001$) extension ($p < 0.001$), ankle plantarflexion ($p < 0.001$) and dorsiflexion ($p < 0.001$) (125).

2.3.4 Physiological changes in musculoskeletal system associated with ageing

Multiple studies have shown that physiological changes in the musculoskeletal system are associated with ageing (126,127). Significant among these are a loss of muscle mass and function (ultimately leading to sarcopenia) as well as osteoporosis, which is decreased bone density (128–130), and osteoarthritis (131). Both can increase disability and are related to high risk of falls and fractures in the hip, spine, and other skeletal sites (132–135).

In addition to structural changes occurring in muscle fibres, bones, and joints, there is also a decreased flexibility in tendons and ligaments which can lead to strains and sprains, and all contribute to the functional impairment that occurs because of these limitations (127,136,137).

2.3.5 Walking in older adults at risk of falls

Limited balance and walking can be associated with ageing because of the changes and deterioration in neuromuscular function (138). A study of 17 younger adults (18 to 24) and eight older adults (65 to 80 years) showed that the control of centre of mass acceleration on an unstable surface was correlated with age, especially in the mediolateral direction (139). In addition to sensory-motor changes, cognitive impairment, especially in attention and executive function was found to have an impact on balance control and walking for older adults (140). Therefore, walking safely in the community requires the ability to undertake concurrent tasks (e.g. dual task) (141).

A recent study by Raffegeau et al (2022) investigating the dual task (DT) in older adults vs younger adults found that older adults have more of a tendency to preserve stability for balance control when performing a “cross the obstacles task” under cognitive demands (141). Having difficulty in avoiding obstacles when walking at a regular pace can be an indicator of fall risk, and this suggests the need for more individualised assessment and treatment.

2.4 Types of strokes according to location

Ischemic strokes are more common than haemorrhagic strokes, and can occur due to large-vessel atherosclerosis, aorto-cardio-embolism, and small-vessel occlusion. Haemorrhagic strokes are most often due to hypertension but may be caused by specific blood vessel abnormalities and other medical problems (142). The clinical impact of a stroke depends on the stroke’s location in the brain, whether it is ischemic or haemorrhagic, and the size/severity of the stroke itself (142).

2.4.1 Stroke in middle cerebral artery

The middle cerebral artery is the most common artery involved in acute stroke. It branches directly from the internal carotid artery and consists of four main branches, M1, M2, M3, and M4 (Figure 2-5). These vessels provide blood supply to parts of the frontal, temporal, and parietal lobes of the brain, as well as deeper structures including the caudate, internal capsule, and thalamus (143). A study by Leys et al screened 272 consecutive unselected patients within 12 hours after a first acute cerebrovascular event and found that 41.2% had a middle cerebral artery infarct (144).

Generally, a stroke involving the premotor cortex reduces the motor outcomes (145). A cerebral stroke at a deeper level called a lacunar stroke - usually has an absence of cortical deficits such as seizures, aphasia, agnosia, and dysgraphia. Classic lacunar stroke syndrome that arises from internal capsule lesions, affects the motor cortex, and patients are commonly presented with ataxic hemiparesis, and clumsy hand-dysarthria (146).

2.4.2 Stroke in posterior cerebral artery

Posterior circulation ischaemic strokes account for 20–25% of all ischaemic strokes. Common associated symptoms are vertigo, visual and sensory/motor disturbances (147). A study by Ng et al screened 89 patients with posterior cerebral artery strokes and found that the most common impairments were motor paresis (65%), followed by visual field defects (54%) and confusion or agitation (43%) (148). Specifically, 72% of those who had had a posterior circulation stroke demonstrated transient vestibular symptoms during the first 3 months of stroke onset, which include dizziness, vertigo, headache, and tinnitus, in addition to limb weakness, sensory change, dysarthria, visual field defect, and diplopia (149).

The main sites of vestibular syndrome caused by ischemic stroke are the insular cortex and posterior thalamus (150). A study by Choy et al (1980) found that, in a cohort of stroke survivors aged between 45 and 75, who had experienced a stroke in the posterior cerebral circulation up to 15 months previously had verticality perception problems and were more sensitive to motion and prolonged duration of nystagmus following rotation, which indicates vestibular system dysfunction (151).

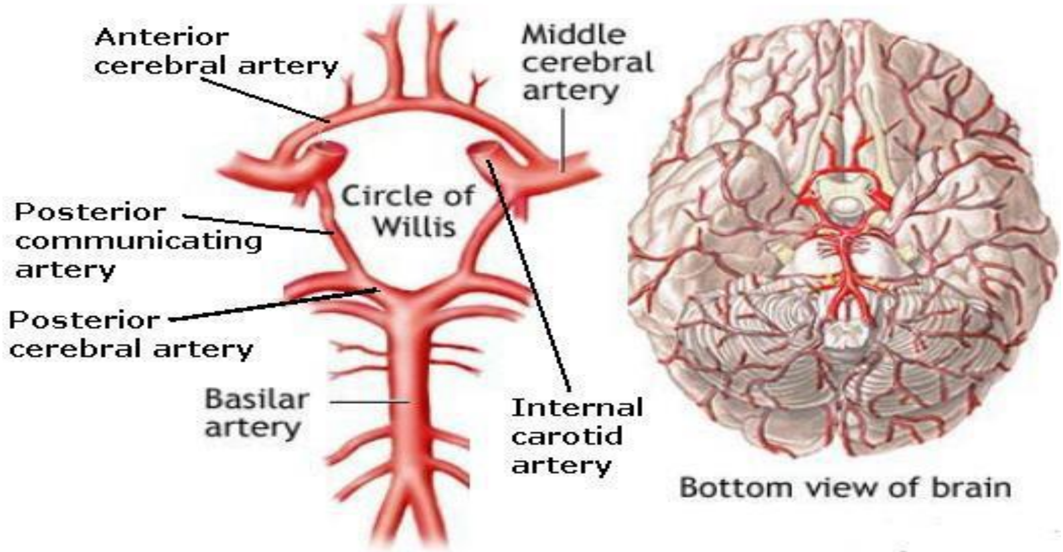


Figure 2—5 Major cerebral arteries- Circle of Willis (posterior left side) (152).

2.4.3 Stroke in cerebellar arteries

Cerebellar stroke may present in a separate way from a common stroke originating in the anterior cerebral circulation. It can initially mimic benign vestibular neuritis and may later deteriorate into a life-threatening neurologic state (153). Cerebellar stroke can result in unsteady walking, feeling of spinning in a still position, balance problems, muscle weakness or tremors, headache, and problems with chewing, swallowing, and speaking. In addition, it can result in problems with sensing pain and temperature, nausea and vomiting, hearing and vision problems, and can lead to loss of consciousness (153).

The posterior inferior cerebellar artery (PCA) plays a key role in the blood supply of cerebellum, and it is the most common area of cerebellar ischemic stroke (Figure 2-6), accounting for 40% of incidents. Stroke in the PCA can lead to vertigo, nausea, vomiting and postural instability because of inadequate blood flow of vestibulo-cerebellum. Meanwhile, infarcts in the lateral branch of the PCA could cause dysmetria and hypotonia of the ipsilateral limb (154).

Cerebellar infarction in the territory of the anterior inferior cerebellar artery can result in acute hearing loss, but infarction in the posterior inferior cerebellar artery territory rarely causes acute hearing loss (155). Strokes involving the brainstem and cerebellum result in acute vestibular syndrome, and acute isolated audio-vestibular loss which may indicate impending infarction in the territory of the anterior inferior cerebellar artery (156,157).

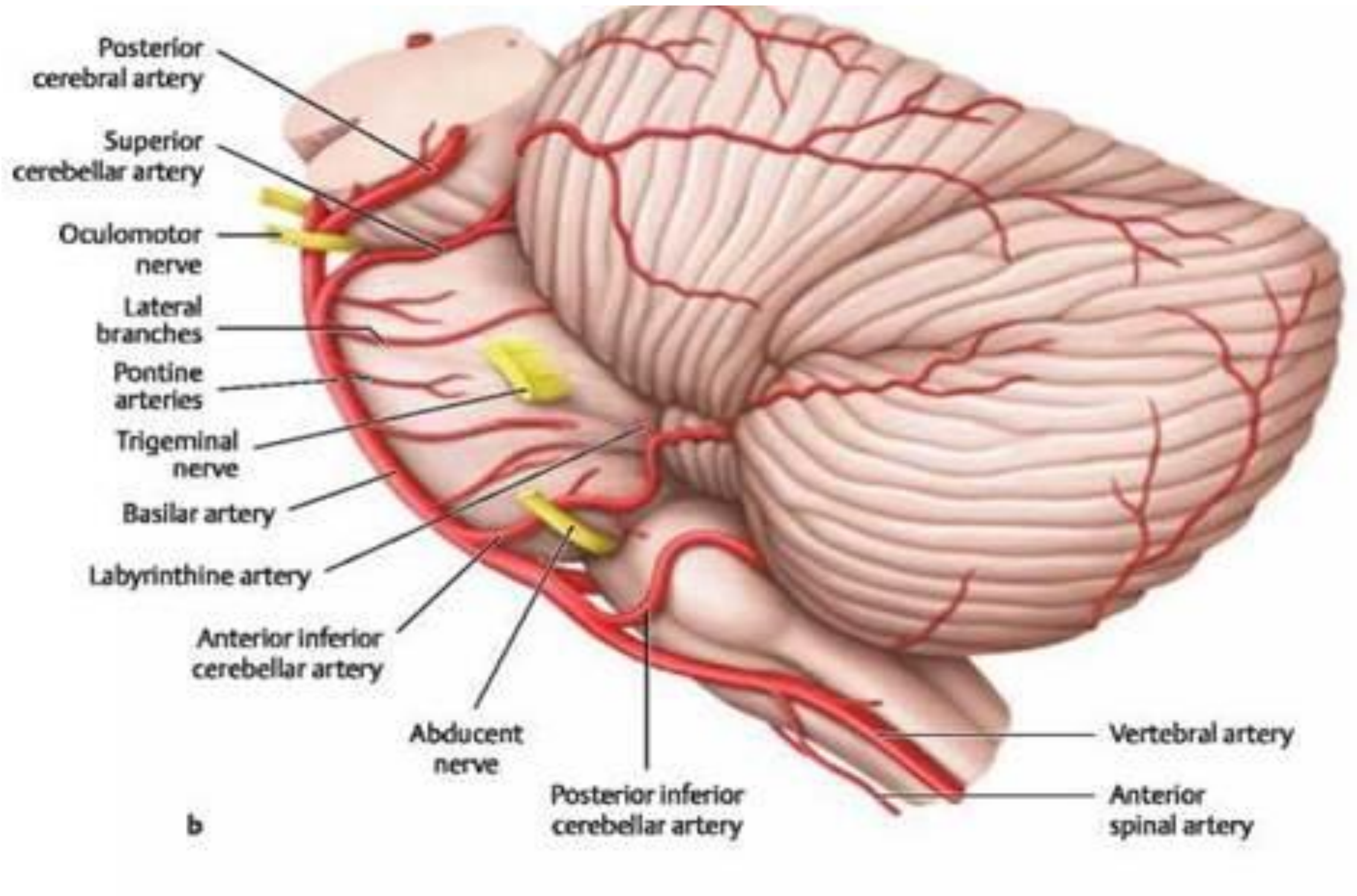


Figure 2—6 Arteries of the brainstem and cerebellum (left lateral view) (152).

2.5 Impairments and dysfunctions after stroke

2.5.1 Sensory impairments after stroke

2.5.1.1 Vestibular system dysfunction associated with stroke

Vestibular problems in stroke survivors can occur due to the interruption of blood flow to the brainstem or cerebellum, impacting the vestibular system. This can lead to symptoms such as vertigo, dizziness, imbalance, and nausea. The common central causes of vestibulopathy are vertebrobasilar transient ischemic attack and acute ischemic stroke involving the vestibular nerve tracts, cerebellum, or brainstem. Haemorrhagic strokes affecting the brainstem and cerebellum have similar symptoms to peripheral vestibular dysfunction: vertigo, nystagmus, nausea and vomiting, and gait disturbances (158).

A study by Zwergal et al (2020) found that 10% of cases with dizziness and vertigo were related to cerebellar dizziness, which represent a large group of disorders with acute stroke or chronic degenerative cerebellar ataxias, and recurrent episodic ataxias. Patients with cerebellar dizziness and vertigo usually show a pattern of deficits in smooth movement, gaze-holding, saccade accuracy, or fixation-suppression of the vestibulo-ocular reflex (159). In addition to stroke in posterior cerebral artery and subcortical level (cerebellum and brainstem), middle cerebral artery territory infarction can cause injury in the vestibular tract to the parieto-insular vestibular cortex which is demonstrated in patients as a typical central vestibular disorder and exhibited as typical ataxia, with several vestibular signs such as vertigo, dysarthria, and dysphagia (160).

2.5.1.2 Hearing disturbances associated with stroke

Stroke can disturb the auditory tract and lead to hearing deficits (161). Major parts of the auditory pathway, such as the cochlear nucleus, inferior colliculus, and medial geniculate body can be affected by stroke. Widespread bilateral lesions of the auditory system typically render the patient unable to respond. When cerebral stroke includes the auditory system, it will result in several types of auditory disorders, and most hemispherical lesions produce subtle hearing dysfunctions (99). These hearing disturbances affect communication, rehabilitation, social engagement, and quality of life (161). Therefore, it is important to add hearing screening in stroke rehabilitation (162).

2.5.1.3 Impairment in proprioception associated with stroke

Proprioceptive information to control balance is also affected by stroke, and stroke survivors have impaired proprioception (163). Impairment in proprioception is associated with increased postural sway, alterations in the centre of pressure excursion due to sensory alteration during quiet standing or gait (164). This indicates that sensory impairment after a stroke affects the neuromuscular activity, which is necessary for balance control (165).

2.5.1.4 Subjective visual verticality and visual dependency in stroke survivors

Studies have shown that stroke survivors can have difficulties in sensory-reweighting because of sensory impairments which leads to exacerbated visual verticality – visual dependency – as a compensatory mechanism to help in correcting posture balance control (93,166). In a cohort study of 30 acute stroke survivors, 60% were shown to have SVV of more than 2 degrees, which exceeds the normal range, and there was no difference in SVV between left or right hemisphere lesions, with both being frequently abnormal. However, recovery after 6 months was higher in left side lesions (96).

The direction of SVV was contra-lesioned in all participants except in two stroke survivors who had lesions in larger cerebral areas (96). The SVV was significantly higher in stroke survivors with spatial visual neglect than stroke survivors without spatial neglect at 45 days and 3 months after stroke period but there was no difference after 6 months (96). Since spatial neglect in acute stroke survivors can affect head and eye posture this can result in head deviation to one side and horizontal eye movement (167).

Stroke survivors during the acute phase have been found to be more dependent on visual inputs and have more difficulty in compensating with somatosensory cues to restore balance compared to healthy controls (168). Additionally, in acute stroke survivors, vestibular cues were found to be correlated negatively with the BBS (Pearson's correlation = -0.58), as well as with visual cues, which had a correlation with BBS of -0.50 (166).

Stroke lesions in the dominant hemisphere can cause more frequent and severe disorders such as spatial neglect and pusher syndrome (169–171). Furthermore, lesions in large arteries such as the carotid artery territory (shown in Figure 2-7) which supplies the anterior and lateral cerebral hemisphere can results in key clinical problems involve occlusion of either the extracranial internal carotid artery or its intracranial branches, including the ophthalmic artery, middle cerebral artery, or anterior cerebral artery (172). A study by Pimentel et al (2019) found that among the 50 different types of stroke, ischemic stroke in the carotid artery territory is the most common stroke type associated with dizziness and imbalance (173).

However, the association between visual vertical and balance control in chronic stroke survivors has not yet been investigated.

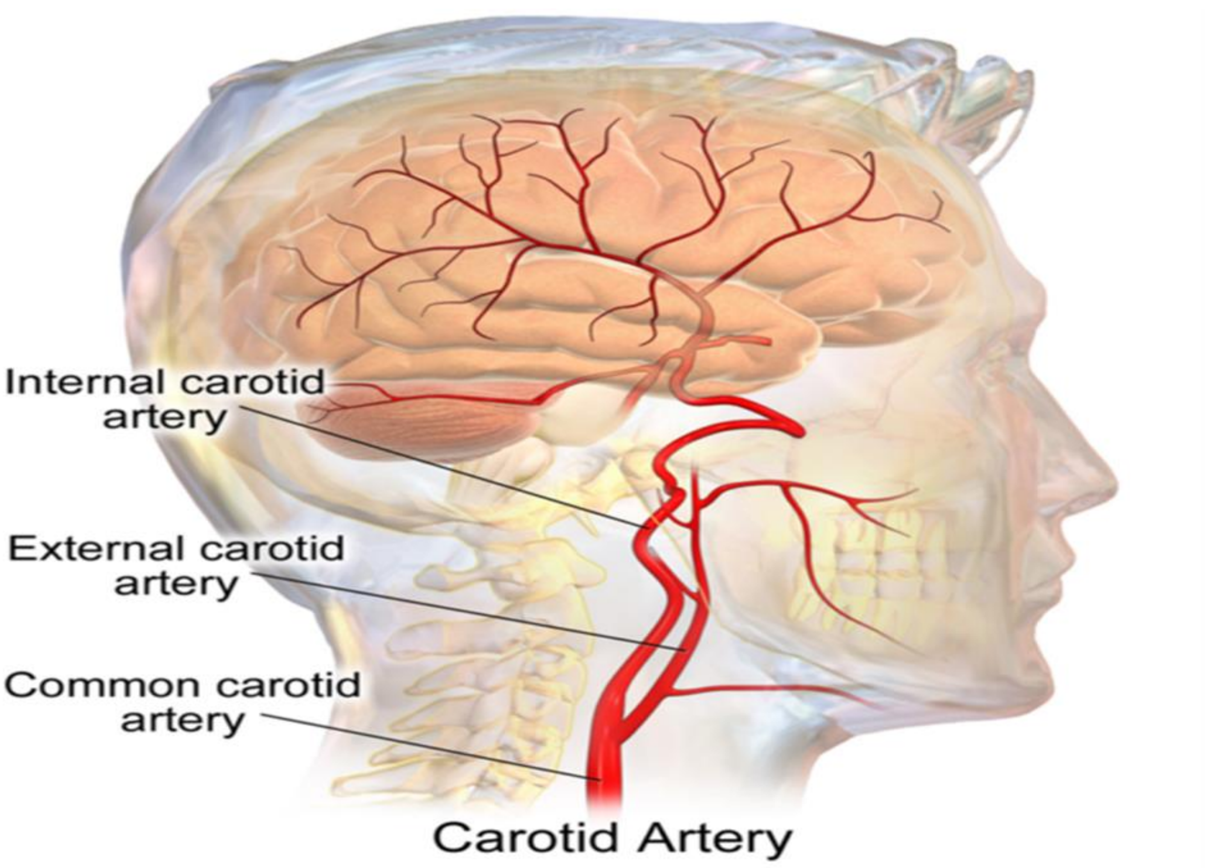


Figure 2—7 Carotid artery and carotid artery territory (internal and external carotid artery) (174).

2.5.1.5 Motor impairments after stroke

Stroke results in motor sequelae that can lead to difficulty in walking, controlling balance while standing and performing daily tasks, and increasing the risk of falls (39). The level of motor impairment is a predictor of functional recovery in physical rehabilitation (175). Motor impairment in the paretic lower limb can be attributed to physiological changes, passive or active restraint of agonist activation, and abnormal muscle activation patterns such as fewer functioning motor units and decreased motor unit firing rates. This results in increase passive tone, altered motor control, and abnormal co-activation, which reduce muscle force generation, increase joint stiffness, and affects postural stability (176). The coordination between agonist and antagonist muscle contraction can be affected by weakness or spasticity in stroke survivors (further explanation is provided in the following section "2.5.1.6 Spasticity").

Additionally, the effect of stroke can have excessive manifestations in the nervous system. For instance, in one new experimental study by Li et al, it was found that altered excitability of motor neuron pathways in five male cynomolgus monkeys with ischaemic stroke at 12 weeks post stroke affected lower motor neuron pathways, and this was not restricted to traditional upper motor neuron impairments (i.e., lesion in the motor cortex). In addition, a disturbed structure and loose arrangement of myelin sheaths were observed in the paretic side median nerve (177). Although this was a small study with preliminary findings, it shows that lower neuronal pathways can also be affected after a stroke.

2.5.1.6 Spasticity

Spasticity is a common complication after stroke, and predictive analysis has shown that 75% of the stroke survivors might develop spasticity within the first 12 months after stroke (178). It is defined clinically by increased muscle tone and tendon jerk hyperreflexia at rest and leading to a decrease in joint range of motion (179–182). Stroke results in an imbalance of inhibitory and excitatory nerve impulses, which result in various degrees of spasticity depending on the location and extent of the stroke lesions. The onset of spasticity may occur within a few days or more than 1 year after a stroke (183). The severity of spasticity is associated with stroke location; the grey matter regions of the insula, basal ganglia, and thalamus, and the white matter tracts in the pontine crossing tract, corticospinal tract, internal capsule, corona radiata, external capsule, and the superior fronto-occipital fasciculus are the dominant areas associated with spasticity (184).

Several factors have been shown to be associated with the presence of spasticity including early severe limb weakness, left-sided weakness, early reduction in activities of daily living, a history of smoking (183), in addition to older age and in haemorrhagic stroke (185). However, another recent study by Béseler Soto et al which screened 554 stroke survivors, found motor index to be the main independent predictor of spasticity, and spasticity as more likely to develop in stroke survivors with sensory impairment and with low Barthel index score (which assesses activity of daily living) (186).

Spasticity is most common in the anti-gravity muscles (i.e., which move the limb against gravity), while the severity of spasticity increased over time in the upper limb more than in the lower limb (187). Spasticity reduces the ability to perform daily activities and increases the burden of stroke (188). As a result of spasticity, other joints will combine as associated movement reactions in the paretic side when moving the sound side (less affected by stroke) or with involuntary movements such as sneezing. Such movement can be associated with flexors or extensors synergies and can be found more predominantly in proximal (shoulder) than in distal (elbow/ wrist) joints (189). In addition, spasticity can increase fall incidence. In a study of 100 stroke survivors, a spasticity score of 2 in the Ashworth scale (which means that a limb has a marked increase in tone but is easily flexed), predicted multiple falls less than a year after stroke ($p<0.008$) (190). Furthermore, the level of spasticity in the gastrocnemius muscle was found to be an independent factor associated with incidence of falls (191).

Generally, stroke survivors who had more severe lower limb spasticity exhibited greater deficits in balance control with poor spatial symmetry and deceleration in the rate of balance control recovery (192). A study by Rahimzadeh-Khiabani et al (2016) of stroke survivors (n=27) found that those with high spasticity had greater predominant challenges in balance control in the mediolateral direction especially in the absence of vision (193). Although studies with a larger sample are needed to identify the impact of spasticity on balance control, Rahimzadeh-Khiabani's et al (2016) study indicates the importance of assessing the balance control under mediolateral perturbation when performing a balance assessment. Accordingly, it can be recommended to include strategies to improve balance control in the mediolateral direction in treatment plans.

2.5.2 Other problems after stroke

2.5.2.1 Cognitive impairment

Cognitive impairment is common after stroke (194–198) and can include, or be associated with, infraction, white matter changes and atrophy, and can lead to vascular cognitive impairment (199). Cognitive impairment can be also present in mild stroke (200). Even in small size stroke lesions such as in lacunar stroke (i.e., a type of ischemic stroke that affects one of the small deep cerebral arteries), the deep location of the stroke in the cerebrum (i.e., at the subcortical level such as internal capsule, thalamus, and basal ganglia) can result in cognitive impairment and dementia (201).

Cognitive impairment after stroke is associated with age, educational level, cognitive status before the stroke, temporal lobe atrophy, white matter changes, and cardiac pathology (199). In a study of group of stroke survivors with cognitive impairment as assessed by the Montreal Cognitive Assessment (MoCA <25), 61% continued to have cognitive impairment after 10 years (202). Cognitive level can interfere with balance control, functional gait, and dual tasking in stroke survivors (203). Stroke survivors who have cognitive impairment including medial temporal lope atrophy and lesions in the white matter had lower balance scores and walking speeds compared to stroke survivors with no cognitive impairment (204).

Essential cognitive function such as working memory (i.e., the ability to retain task-relevant information), attention (i.e., to selectively process information in the environment), and executive function (i.e., ability to organise thoughts, prioritise tasks and make decisions) are required to perform complex motor tasks, such as walking at a functional level (205). The amount of attention that is required for postural control depends on the individual, the nature of the task performed, and the environment (21,22).

Attention is not a unitary resource; therefore, dual tasking activities can be performed, for example, walking while simultaneously practising a concurrent cognitive task, or a manual task (206). However, each person has a finite attention span, therefore if there is more than one target to achieve (for example cognitive task), this can suppress other tasks (for example walking) and can produce mutual target-target interference (207). Prioritising or dividing attention for more than one task relies on personal selection (207).

There are various scenarios that result in deterioration of one of the tasks during the performance of DT walking. For example, one possible scenario could be that motor performance remains stable while cognitive performance deteriorates, or the opposite (203). In stroke survivors, deterioration can be presented in a decrease in gait speed or a suspension of motor performance and/or a decrease or suspension in cognitive performance (208).

The level of cognitive function can be associated with the level of motor function. A recent study of 567 acute stroke survivors found that cognitive tests (MoCA, Trail Making Test Part B and 10-Word List Recall) were associated with grip strength and Short Physical Performance Battery (209).

2.5.2.2 Psychological problems

Regardless of the severity of cognitive impairment, psychological symptoms, especially depression, are highly prevalent among stroke survivors (40%) (210). The effect of stroke on psychological status can persist for a long time. Longitudinal studies have found that 2 years after stroke, patients had less proactive coping, lower self-efficacy, less extraversion, and less optimism (211). Furthermore, 15 years after stroke, 39% of survivors had depression and 35% had anxiety (212).

Mood and emotional disturbance are also common, which leads to distress, embarrassment and decreases patients' quality of life (213). The lack of, and difficulty in, psychological status assessment have been noted by Harrison et al (2017), highlighting the need for improving support for patients (214). All the psychological problems listed can affect social activity and relationships (215). In working-age (18-65 years) stroke survivors, well-being and satisfaction with social roles and activities have also been shown to be low when assessed by the Patient-Reported Outcomes Measurement Information System and the Quality of Life in Neurological Disorders measurement system (216).

Unstable psychological status associated with stroke has been found to impact mobility (217). For instance, one study found that in acute stroke survivors, self-esteem instability and depression were associated with low mobility functioning (218). Increased fall-related self-efficacy and Health-related Quality of Life have also been associated with decreased mobility (219). In addition, stroke survivors with depression have been found to have less gait recovery after a gait rehabilitation programme compared to those with no depression (220). However, there are few studies on the association between psychological symptoms - such as depression, anxiety, illness perception – and walking at a functional level in chronic stroke survivors.

2.5.2.3 Sleep disorders

Sleep is one of the important physiological needs to relieve physical and mental fatigue, and to regulate metabolism and improve memory. Sleep also helps in tissue regeneration, synaptic stability, and immune regulation (221–224). Approximately 53% of stroke survivors have reported poor sleep quality (225)**.** Common types of sleep disturbance in stroke include a) insomnia (sleep reduction and difficulty in starting or maintaining sleep); b) hypersomnia (excessive daytime sleepiness); c) breathing-related sleep disorders (including obstructive sleep apnea, central sleep apnea, sleep-related hypoventilation, and circadian rhythm sleep-wake disorders), and d) parasomnias sleep arousal and nightmare disorders) (226,227).

The causes of sleep disturbance can be related to brain lesions after a stroke, depression, and environmental factors (226). Furthermore, sleep quality is closely related to cognitive function and psychological status; in a cohort study of 530 stroke survivors, linear regression showed that the effect of cognitive function (assessed by MoCA test) on quality of sleep (i.e., Pittsburgh Sleep Quality Index) was $\beta = -0.27$, where decreased MoCA scores affect quality of sleep negatively in 0.27 points. Similarly, the effect of anxiety (i.e., Self-Rating Anxiety Scale) and depression (i.e., Self-Rating Depression Scale) on sleep status was $\beta=0.23$, and $\beta=-0.18$, respectively (228). Location of stroke may also play a role with one study on stroke survivors during the hospitalisation period finding that increased daytime sleepiness was associated with subcortical lesion location, fatigue, and quality of night-time sleep (229).

In one study undertaken within one month of rehabilitation, 25% of stroke survivors had sleep disturbances, which in turn affected balance and gait patterns negatively (balance was assessed by the BBS and gait was assessed by 10-metre walk test) (230). However, the association between sleep disorder and balance/functional walking in chronic stroke survivors has yet to be investigated.

A cohort study of stroke survivors showed that there is an association between moderate to vigorous physical activity (PA) levels and sleep efficiency, with more time spent in moderate to vigorous PA meaning better sleep quality. However, this change is small; with 10 minutes of moderate to vigorous PA, the efficacy of sleep is increased by only 0.01 point (231). This study used a series of multivariate linear regression models on a small sample size (n=40), however a larger sample size for a linear regression model has been recommended (232,233). In general, PA and exercises are associated positively with sleep in older adults; exercise promotes sleep efficiency and duration (234,235). The association between sleep and PA in stroke survivors remains unclear, therefore, more studies are required for stroke survivors to investigate the association between sleep and PA.

2.5.3 Walking ability after stroke

In a study by Louie et al (2022) of the acute stage (within 48 hours) after stroke, lower limb motor impairment and walking limitation were measured using the National Institutes of Health Stroke Scale and the Functional Independence Measure (FIM), respectively, for 487 stroke survivors. The results revealed that 44% of stroke survivors have lower limb motor impairment and 46% were unable to walk (236). Louie et al (2022) study's showed that a high percentage of stroke survivors were unable to walk albeit they have no severe motor impairment based on the clinical tests. In another study by Kubo et al (2022) for subacute stage (3 to 6 months) after stroke, the average daily number of steps was 4,286 steps only

(237). Reinholdsson et al (2021) found that improving in walking ability after stroke was quicker in pre-stroke physically active people (238).

Fundamental factors for independence walking after stroke were knee extensor strength and proprioception on the affected side, in addition to trunk muscle strength (16,41,239,240). Walking ability after stroke is limited by motor deficit which can result in pathological muscle synergies (241). Muscle synergy is defined as the coordinated recruitment of a group of muscles with specific activation, however, pathological muscle synergies are associated with constraints on movement in stroke survivors (241). Although, pathological muscle synergy in the lower limbs can limit walking ability, it can help to produce maximum hip extensor torque and has been found to have an association with gait speed (i.e., Timed Up and Go (TUG) test) (242).

Other factors such as visuospatial perception and cognitive function have an influence on walking ability as well (16,41,239,240). Spatial navigation even after a mild stroke can deteriorate walking ability, with Hamre et al (243) finding that nearly one in four stroke survivors experienced difficulties in spatial navigation. Hamre et al (243) identified that spatial navigation was associated with stroke characteristics such as severity and cerebral location, cognitive ability (i.e., memory and executive function), and gait speed as assessed by a 6-minute walk test (243).

Despite all the difficulties facing ambulatory stroke survivors in walking, safety in walking is the most crucial difficulty to overcome. Stroke survivors learn to develop adaptability processes such as deliberately avoiding obstacles or making sudden stops while walking (244). Therefore, walking adaptability scores have been found to be negatively correlated with spatiotemporal gait parameters (i.e., gait speed) (244). A walking adaptability strategy can be used to prevent a fall (245), yet return to independent walking is a requirement for optimal functional activity after stroke (246). A lower level of walking ability was found to be positively associated with lower self-efficacy, and lower cognitive scores (i.e., MoCA test) in a group of chronic stroke survivors (247), with walking ability being evaluated in the latter study by the 6-minute walk test and gait speed. Even though gait speed is a crucial factor for walking, there is a need to include other elements in day-to-day normal walking, as functional tasks are often required whilst walking.

2.5.3.1 Walking at a functional level in stroke survivors

About 85% of stroke survivors regain their walking ability with or without the use of an assistive device, however only 45% recover their independence in day-to-day activities (44). In a study by Lord et al (57), 74.6% of stroke survivors considered the ability to "get out and about" in the community to be either essential or particularly important (57). Limitations in walking have been shown to increase the risk of being housebound and isolated (206) and reduces social participation (15). Slower return to independent walking has been related to older age, diabetes, severe haemorrhagic stroke, and right hemisphere stroke (248).

It has been also identified that impaired body orientation with respect to gravity is more frequent in right hemisphere stroke in the subacute stage (249). Stroke survivors who experience slow progress in real-world walking expressed negative emotions (55). In addition, reduced community walking is associated with fewer encounters and greater avoidance in the dimensions of the Environmental Analysis of Mobility Questionnaire, such as walking multiple trips and over different terrain (250).

Community walking requires high functional gait performance (251), which refers to the capacity to integrate multiple physical and cognitive function, such as walking carrying bags or walking in a supermarket while reading the groceries prices (78). Meanwhile, gait speed is a fundamental component of functional gait and allows people to perform important tasks such as crossing the road in an efficient way and in sufficient time. The ability to walk at maximum speed was not associated with age, gender, or time post-stroke, however it was negatively associated with the degree of disability (252).

A study by Awad et al (2023) of 7 stroke survivors found that they usually walked at a speed slower than their maximum to allow more stability - which was measured by the mediolateral motion of the pelvic centre of mass (253). Although Awad et al (2023) only studied seven stroke survivors, they demonstrated that to improve walking speed there is a need to improve pelvic stability. Another study by Kong et al (2015) found that walking speed is associated with pelvis alignment, since difference between both sides in anterior superior iliac spine has a moderate positive association with gait speed in a 10-metre walk test (254).

A recent study by Chow et al (2023) found that temporospatial parameters including initial double-support, single-support times, and step cadence were longer in stroke survivors walking at slow speed (<40 cm/seconds) compared to higher speed (>80 cm/seconds) (255). Stroke survivors who experienced falls had a slow gait speed of 0.67m/seconds, however non fallers had a speed of 0.74m/seconds (64). Furthermore, a positive association was identified between 6-minute walk test and distance in stroke survivors who had distance decline after minute 1 in the 6-minute walk test, while there was no association in stroke survivors whose distances did not decline (256).

Additionally, gait speed had a positive association with functional capacity assessed by the Duke Activity Status Index in metabolic equivalent (i.e., the rate at which a person expends energy), and was calculated by the maximum oxygen uptake (VO2) (257). Similarly, gait speed had a positive association with the quality of joint movement during walking assessed by the Gait Profile Score (258) and with balance control assessed by the BBS (239). Gait speed was the strongest predictor of community walking in a cohort of stroke survivors; a comfortable gait speed of 0.93 m/seconds was identified to discriminate between limited community and full community stroke ambulators (54). Furthermore, a recent study by Avelino et al (2022) showed that gait speed and hip muscle strength can indicate better walking outcomes (259).

In addition to gait speed, there is a need to be able to perform complex motor tasks while walking, for example turning one’s head, walking on a narrow base of support, or walking up/downstairs (260). Furthermore, walking on different terrains has been identified to be challenging and requires more adaptability from stroke survivors (261). They often have difficulty or inability in performing required modifications to maintain stability and safety when walking on different terrains, which includes lowering the centre of mass, increased muscle co-contraction during stance and exaggerated or increased toe clearance during the swing phase (261).

The ability to perform functional gait also includes undertaking a secondary task while walking, which can be a motor or cognitive task (i.e., DT while walking). The limitations in functional gait performance will result in a decline in either the motor or cognitive performance in DT situations or in both tasks (262).

Notably, walking at a functional level is also influenced by muscle strength, balance, and cardiovascular endurance (263). Additionally, a few studies indicate that walking in the community in stroke survivors can be associated with subjective factors such as self-efficacy (263) and psychological status (219). In addition, cognitive ability may adversely affect balance and gait speed in acute stroke survivors with moderate cognitive dysfunction (264). However, it is not clear if mild cognitive dysfunction in chronic stroke is associated with functional gait.

2.5.3.2 Physical activity

Physical activity (PA) includes any energy expenditure that results from skeletal muscles movement (265), this includes aerobic activity and muscle-strengthening activity (266). Meanwhile, the intensity of PA is strongly associated with physical capacity such as the 10-metre walk test (267). It is widely documented that stroke survivors have lower PA levels than age-matched healthy adults (268). Low PA levels in stroke survivors is related to poorer walking ability, and impairment in sensorimotor functions (56). In addition, a study by Gothe et al (2020) found that the intensity of PA was associated with the level of upper and lower limb function (269).

The National Institute for Health and Care Excellence (NICE) recommends that PA is crucial for poststroke recovery (270). Incorporating PA in stroke rehabilitation has also been recommended by the American Stroke Association to increase physical functioning (269). Meanwhile, the importance of PA extends to preventing secondary complications related to recurrent stroke and other cerebrovascular diseases (266). Plenty of evidence also confirms that PA helps to maintain motor functional autonomy and improves quality of life

(53,271,272), enhancing the neuroplasticity after stroke, which can also help with cognitive ability (273).

A previous systematic review included 16 studies focused on aerobic training with moderate to intense PA, such as repetitive treadmill training or exercise on a stationary bike, for 8-weeks in duration (274). This showed that such activity increases the neuronal network and neuroplasticity, since moderate to intense exercise can stimulate neurophysiological and vascular changes in the CNS (274). However, not all included studies in the review used the functional magnetic imaging (fMRI) for assessing neuroplasticity, but instead used scales to assess motor functioning (such as the Fugl Meyer scale) or to assess cognitive function (274).

Remarkably, increased brain activity in the bilateral primary sensorimotor cortices, the cingulate motor areas, and the caudate nuclei bilaterally and in the thalamus of the affected hemisphere have been identified after walking on a treadmill over 12 sessions of 45 minutes in a sample of 18 ambulatory chronic stroke survivors (275). Higher intensity of PA led to greater neuroplasticity, since higher intensity forced exercise led to rapid increase of brain-derived neurotrophic factors (276), and helps in improving social interaction after stroke (277).

Despite all the known benefits of PA for stroke survivors, the level of PA among stroke survivors is low, and low rates of compliance with exercise have been noted (278–280). Stroke survivors face plenty of barriers, and often lack the ability or the skill to perform an activity (281,282). A recent study screened 2000 stroke survivors in the UK and identified that the main barriers to engaging in leisure activities were physical difficulties (69% of respondents), low energy levels (17%), loss of independence (11%), psychological difficulties (10%) and low mood, fears, and anxiety (283). Inactive physical (i.e., prolonged sitting) time was associated negatively with self-reported physical function (Stroke Impact Scale) and walking speed (284). Although it is known that there is a strong positive association between PA and physical ability (265), the association between PA and psychological status and cognitive function has not been meaningfully studied in ambulatory stroke survivors.

In summary, physical, cognitive, and psychological impairments in older adults at risk of falls, and in stroke survivors have been discussed in this section, in addition to the importance of walking at a functional level. The assessment of balance and functional gait and strategies of treatment used for older adults at risk of falls and stroke rehabilitation will be discussed in the following sections.

2.6 Assessment of walking at functional level

For optimal physical rehabilitation, the assessment needs to cover physiological impairments to address the underlying causes (51). Additionally, assessment should include functional limitations and address the consequence of these limitations to help in setting the goals of treatment (51). This section will provide a summary of outcome measures (OM), which are widely used for balance and functional gait assessment in stroke rehabilitation.

Examples of OM used for assessing balance in sitting, standing, or shifting the weight from standing (static balance) are the Tinetti balance and gait assessment scale, and the functional reach test, which both have good reliability, the Intraclass Correlation Coefficient ICC= 0.85, 0.90, respectively (51,285,286). Furthermore, to assess the sensory integration for balance control when standing, sensory integration tests can be used, since these tests assess the ability to maintain a standing position in six conditions from typical standing to more challenging positions involving having one’s eyes closed and standing on different platforms (43).

Meanwhile, to test sensory-motor function and reaction time, the Physiological Profile Approach (PPA) can be used. The PPA has a good validity and reliability and is used to assess the risk of falls (287,288). The most commonly OM for the assessment of balance control is the BBS which has high reliability and validity and includes assessment of static balance in addition to simple tasks related to dynamic balance such as turning (289). However, it does not include tasks to test balance while walking, therefore its sensitivity decreased for ambulatory individuals (290). In addition, the TUG test, has a high reliability and is quick to perform (291), but the main outcome from the test is the walking speed in seconds and it does not test balance in walking.

Furthermore, the Balance Evaluation System Test (BESTest) has recently been developed and can be used to identify the cause of balance impairment and includes tasks to test balance in walking. It is an intensive test that covers varied factors contributing to balance, including biomechanical constraints, stability limits, anticipatory postural adjustments, postural responses, sensory orientation, and stability in gait (292). The BESTest has been validated for stroke survivors and has high reliability and validity (293); however, it can be time consuming, therefore a short form of the test (Mini-BEST test) has been developed (292,294).

Balance in walking can also be assessed by the Dynamic Gait Index (DGI) which has a good validity and reliability for chronic stroke survivors (50). Yet, the DGI has a ceiling effect, therefore the Functional Gait Assessment (FGA) scale was developed, which includes more challenging tests, such as walking on a narrow base of support and walking with eyes closed

(295,296). The FGA has a good discriminative and predictive validity, and responsiveness (295,296) and has been tested in ambulatory stroke survivors (297). Furthermore, the FGA has been determined to reflect the spatiotemporal parameters that are required for walking in the community, such as gait speed and the ability to do concurrent motor tasks (i.e., head turns while walking) (260).

In addition to the clinical assessment of balance and functional gait which have been described, laboratory-based tests which require the use of specific equipment can provide comprehensive qualitative data. For example, the use of a computerised system, such as the posturography system, and wearable inertial sensors (13). Both sensory organisation and motor control can be tested in the posturography. In the sensory organisation test, the parameter measured is the patient's anterior and posterior body sway, and this provides six conditions to assess the contribution of sensory (visual, vestibular, somatosensory, and proprioceptive) inputs. The motor control test assesses the automatic postural responses to forward, and backward horizontal movements of the platform and these tests are measured in latency (40,298).

More recently, inertial sensors have been used to help in quantifying biomechanical data. Inertial sensors are devices that measure specific force and angular rate, also, detect motion and orientation (299). Inertial sensors include accelerometers which measure acceleration forces in one, two, or three axes (299). These are commonly used in fitness devices, and automotive applications. Inertial sensors also include gyroscopes which measure the rate of rotation around one or more axes, the gyroscopes help devices maintain orientation and stability (299). Furthermore, Inertial Measurement Units (IMUs) combine accelerometers and gyroscopes in a single unit which provide comprehensive motion tracking system and orientation data. IMUs are used in virtual, augmented reality systems and robotics (299).

A study by Hillier et al (2009) used an insole plantar pressure sensor system, showed that stroke survivors in the hemiplegic side had more contact pressure but less centre of force (300). Moreover, sensors have been used to assess ascending and descending stairs, such as the Magneto-Inertial Measurement Unit (MIMU) sensor worn at sternum level to quantify the trunk sway (301). Data from the MIMU has demonstrated a strong correlation with the DGI (301).

Inertial sensors have shown strong reliability and provide more objective kinematic data (302), however, assessments of balance control in physiotherapy clinical practice by clinical outcome measurements (OM) with no or very minimum cost are used more frequently (303). However, evidence on psychometric properties of clinical outcome measures is scant. Among the available reviews for balance assessment, the focus is on balance in static positions (sitting or standing) covering the preliminary stages of stroke rehabilitation or spatiotemporal aspect of gait (50,51), but not dynamic balance and balance of complex tasks while walking, which is necessary to study in ambulatory stroke survivors.

Multiple studies to assess the intervention for balance control use an OM such as a sit to stand test which was originally developed to assess lower limb muscle strength in functional tasks (304), and had a positive correlation with balance (305–307), however it does not assess dynamic balance. There is thus a need to review OM focused on the assessment of dynamic balance and in walking at a functional level. These OM can be used to assess the improvement in higher functional ability and not limited to gait speed. In Chapter 2, a systematic review is conducted to identify and appraise psychometric properties of clinical OM of walking at a functional level used in stroke rehabilitation.

2.7 Treatment strategies for walking at a functional level

Although causes of stroke may differ, neurological recovery and rehabilitation follow the same principle that lesions in brain tissues can recover over time. Evidence has shown that lesioned brain tissues have a great and fast plasticity, which involves spontaneous rewiring of neural networks and circuits, in addition to improvements in functional responses in neurogenic niches (308,309). The degree of motor impairment and time since stroke determine the changes in neuronal activity (309). However, even in chronic stages, neuroplasticity is more likely to be gained by utilising the surviving structures and networks, which can generate some form of motor signal to spinal cord motor neurons. In addition, some areas develop a new role in motor performance to compensate for the function of the cerebral area affected by stroke (310).

Motor control helps in enhancing the activation of neuroplasticity (311), which not only includes the corticospinal tract, but extends to brainstem pathways and interhemispheric connections, which all help in increasing recovery (309). In a cohort study of 12 stroke survivors with left cerebral hemisphere lesion, there was evidence of neural activation in both ipsi-lesional and contra-lesional premotor as well as contra-lesional motor (M1) regions, after left or right hand or foot movement (312). Although the sample size was small and focused only on left lesions (312), it highlights that neuronal activation took place in both hemispheric sides and includes motor and premotor areas.

To enhance neuroplasticity by motor control to drive a specific function, the dose of motor training needs to be performed in sufficient time and intensity. A minimum dose of 15 hours per week of exercise has been recommended in previous studies (313,314). Moreover, it takes 10-12 weeks to recover the ability to walk safely in the community, which requires challenging functions such as crossing the road in an efficient time (315). As has been suggested in recent studies, to improve mobility in community settings, there is a need to move beyond traditional low-intensity/low-demand rehabilitation (316,317).

Therefore, the treatment goals should be individualised according to the level of impairment and limitations in balance and functional gait for stroke survivors. These treatment goals can be addressed to a) reduce or prevent further balance disorder, b) develop effective strategies to help restore balance in challenging environments (for instance dark areas or uneven surfaces), c) and retrain functional tasks in a wide variety of environmental contexts (such as dual-task walking) (40). Current available treatments are based on performing physiotherapy exercises such as repetitive task training, functional task training, caregiver-mediated exercises, and water-based exercises (307,318). In a study by French et al (2016) repetitive task training which involves task-specific motor activities, showed statistically significant improvement in muscle strength and functional mobility (314). The focus in task-specific motor training is often on a single limb, which can be effective for stroke survivors with severe and moderate motor impairment. However, to optimise functional activities there is a need to integrate more challenging exercises.

Most of the research in this area has focused on basic balance training and simple walking exercises (36). Treatment interventions may also involve the use of electromechanical-assisted gait training, Tai-Chi exercises and interventions for eye movement and visual field defects to improve balance after stroke (307). However, there is insufficient evidence to determine the most effective rehabilitation for dynamic balance impairment and functional gait for stroke survivors (319).

Moderate intensity exercises are recommended to increase gait performance (320), because limited functional walking can increase physical inactivity and decrease fitness level (321). However, common rehabilitation of gait remains of a low intensity, for example a mean of 2460 (SD 1057) steps/session for 30 (±7) sessions was documented as an optimum for young ambulatory adult stroke survivors (<65 years).

In addition to sensory-motor training, since balance requires integration between sensory inputs, rehabilitation should include training of the vestibular system (40,322–324). Although vestibular rehabilitation is recognised as being important, it is rarely addressed for balance rehabilitation in stroke survivors (325). Exercises for the vestibular system should be prescribed according to patient capacity, with various positions graduated from sitting, standing, and walking. Multiple studies have shown that multi-sensory (MSR) exercises led to effective improvement in vestibular function and sensory motor integration, and therefore improvements in balance and functional gait in older adults at risk of falls (80,326–329). MSR exercises can be added to improve balance control for stroke survivors (330). Further explanation of the MSR exercises will be detailed in Chapter 6, section "6.2.5.1.3 The Multi-Sensory Rehabilitation (MSR) exercise".

Furthermore, cognitive training, which plays a role in spatial neglect rehabilitation in stroke survivors (331), needs further investigation for its effect on balance and functional gait. A recent Cochrane review supports adding interactive cognitive training to balance and gait programs, as it encourages engagement and self-empowerment which help in improving physical, psychological, and cognitive skills (332,333) and adherence to exercise (334). The integrated cognitive and motor pathways can promote connectivity and prompt neuroplasticity (335,336).

Another critical issue in stroke rehabilitation is that adherence rates to exercises are recognised to be low. Previous studies have suggested home-based rehabilitation to increase exercise adherence rates (315,337,338). A framework to enhance adherence to home-based exercises after stroke was developed by a Delphi panel consisted of 13 experts which includes patient education on stroke and recovery, method of exercise prescription, feedback and supervision, cognitive remediation and promoting self-efficacy, involvement of family members and society, and motivational and reminder strategies (339). The use of home-based technology including telerehabilitation helps patients to engage with the exercises, increase the motivation (including external and internal motivation) and therefore in adherence to exercises (340). The next section will discuss telerehabilitation for balance training in more depth.

2.7.1 Telerehabilitation for balance training

Telerehabilitation can be defined as interventions to improve a particular functioning of individuals using technologies and telecommunication to provide activities and monitor progress and safety from a distance (14). Telerehabilitation has become an increasingly popular method for delivering rehabilitation services to increase adherence to exercise in an engaging environment. Adherence rates for rehabilitation with VR were found to high compared to traditional home programmes in a review of 22 studies for older adults (341), but the traditional home programmes were not defined in the review.

Telerehabilitation has been used as a substitute to in-person rehabilitation approaches to reduce outpatient resource utilisation, especially for individuals who may have difficulty accessing in-person rehabilitation opportunities, and to cover the demands for people needing physical rehabilitation (70). In addition, the use of telerehabilitation for older adults was predominant during the COVID-19 pandemic (70,342).

Furthermore, studies have shown that telerehabilitation has acceptable feasibility and offers the advantage of promoting adherence to therapy and improved quality of life (343,344). Multiple reviews have shown that for functional measures such as sit-to-stand test, 6-minute walk distance, TUG test, and quality of life telerehabilitation provides similar improvements to face-to-face physiotherapy rehabilitation, while also having lower health-care costs (71,343,345). However, no details were provided in comparison to the traditional rehabilitation services. In addition, most of the studies included in the review were for older populations with additional musculoskeletal and respiratory problems (343).

Interestingly, a recent systematic review by Lee et al (2023) for balance and gait telerehabilitation included 14 studies, 9 studies used smartphone and 5 used tablet technology to provide the exercise. The participants were trained through biofeedback (in 8 studies), followed the recommended exercises (in 4 studies), or with video games (in 2 studies); while the exercises focused on weight shifting from standing. The review identified that improvement in functional movements, cognition, and reduced fear of falling and anxiety levels can be maintained for 4 weeks after the intervention (346).

Older adults are increasingly using telehealth, smartphone apps, and other digital health technologies to reduce barriers to care, maintain patient-provider communication, and promote disease self-management (347). There are a variety of ways of delivering telerehabilitation for physical rehabilitation, including general and specific platforms with real-time videoconferencing technology (348). For example, a study found exercise rehabilitation provided by Zoom conference with a personal computer for a health coach and personal computer/laptop/iPad/phone for patient was feasible and useful in a cohort of 30 older adults (349).

In addition, virtual training with systems using exergames (technologies that promote healthy behaviours by combining video game technologies and exercise) such as the Nintendo Wii or Xbox Kinect increase patient engagement in exercises (350–353). A randomised study by Li et al (2021) assigned 23 participants (aged > 60 years) to Kinect or Wii Bowling exergames for three sessions in one week only. The results indicated that exergames have no or minimal risk, there was a positive attitude and participants very willing to engage. The results also suggested that the Wii might provide a more intense physical activity than the Kinect, while in the Kinect participants' perception about the benefit of exergames was higher than the Wii (353). The sample was not tested for older adults at risk of falls, additionally a general Nintendo Wii and Xbox Kinect programmes were used which cannot be tailored to each individual's needs. There is a need for more specific systems for older adults at risk of falls and for stroke survivors, potentially directing their needs, for example training to enhance dynamic balance control and cognitive motor interference.

2.7.1.1 Telerehabilitation for older adults

Recent studies have investigated telerehabilitation systems using specific platforms for older adult users. An exergame-based telerehabilitation system for older adults called the Continuum-of-Care (COCARE) project has recently been developed (354,355). This system had a good acceptance rating (a mean of 83% in the usability scale), and participants in a previous study expressed good satisfaction with physical and cognitive tasks (355). Participants included in the project were older adults aged ≥60 years and who were able to independently stand for at least 2 minutes, while older adults with difficulties in dynamic balance or at risk of falls were not targeted. Although the COCARE system measures stability by the centre of pressure, trunk or head movement was not measured. In addition, all exercises were from standing only, with no progression to walking. The feasibility of the system was tested only in one session and was not tested for treatment sessions. In addition, no motor functional assessment was undertaken, only the contact pressure from standing on the foam connected to the system was assessed before and after a single session.

An ongoing project called the MULTIPLAT_AGE (https://multiplat-age.it/index.php/en/) which includes information and communication technology for older adults, and provides a transitional care model from the hospital to home area. Also, it includes a telerehabilitation programme to reduce the risk of falls, and remote cognitive stimulation programme (356). One of the ongoing studies by Pilotto et al (2024) emerging from the project is to study the feasibility and efficacy of Action Observation and Exergaming (E-ACTION TRAINING) which uses web-based exergames, a tablet personal computer and the Kinect platform to improve balance and walking for older adults at risk of falls (356).

Another ongoing study from the project involves using a telerehabilitation system (Stimo.TE-Rehab) to assess the efficacy of remotely-delivered cognitive stimulation on cognitive function and activities of daily living for older adults with Parkinson's disease or stroke with moderate cognitive dysfunction (356). Details were provided for participant selection and measurement; however, no details were provided for the exercise programme, and there were no published results.

In a separate development a sensor-based telerehabilitation and telemonitoring system (STASISM) was developed by Kushnir et al (2024) to support an individualised VR system, which is a system which uses a personal computer or laptop to run the rehabilitation program, and requires an internet connection, a web camera, and a balance board (357). The system provides visual feedback for a few physical exercises such as 4-point kneeling (cat position) and was tested only for children with motor disabilities, with no results published yet.

2.7.1.2 Telerehabilitation for stroke survivors

Telerehabilitation was widely used as a therapeutic solution for stroke survivors during the Covid-19 pandemic (358). A review of 10 studies by Ostrowska et al (2021) showed that the use of VR was highly acceptable in stroke survivors to provide exercise and increased motivation to engage in the exercises (358), since it promotes engagement and self-empowerment, which increases positive psychological status (359). The application of VR for stroke rehabilitation is promising for improving motor function for stroke rehabilitation, as reported by a Cochrane review (360). Furthermore, a recent study by Kerr et al (2023) found that the application of VR with treadmills, power-assisted equipment, and balance trainers showed improvement in adherence to exercise by up to 82% in stroke survivors (361).

The advantages of adding VR to balance rehabilitation include providing motivation, enjoyment, and stimulating activity in a safe environment (362). In addition, VR provides intensive task-oriented training which stimulates sensory feedback, motor, and cognitive skills especially attention, visuospatial and executive functions (352,363). The combination of cognitive and motor skills in VR helps in integrating both pathways and promotes neural connectivity (335). In addition, motor-cognition training in simultaneous sessions can reduce the level of fatigue (335). However, most previous studies have focused on the upper limb or hand function with no studies focusing on dynamic balance and gait after stroke.

In older adults at risk of falls, recent studies have shown that adding VR to a rehabilitation programme can aid in improving gait and balance (337,338), and decreases fears and risks of falling in the long term (364). In a cohort study by Cano Porras et al (2019), the use of a VR assisted rehabilitation environment for 12 sessions showed statistically significant improvement in the timed-up and go and 10-metre walk tests, BBS, Mini-BESTest, in addition to improving confidence in balance (365). However, the sample included different neurological conditions and was not specific for stroke survivors, and the exercises were not clearly described, which limits applicability.

A virtual rehabilitation platform called EVOLVRehab using VR, gaming and motion capture has been developed by Evolv Rehabilitation Technologies (https://evolvrehab.com/) (2018) aims to make therapy more enjoyable (366). In a cohort study by Morse (2022) of stroke survivors who experienced spatial neglect it was shown that this system was acceptable and provided performance feedback, engagement, and enjoyment, as well as psychological benefits associated with self-administered VR telerehabilitation (367). Another study of EVOLVRehab by Ellis (2022) showed that the mean adherence rate to the exercise programme for motor recovery in the upper limbs for stroke survivors was good (87.5%) (368).

Furthermore, a recent scoping review for the use of technology (wearable devices, VR, robotics, and exergaming) to improve movement in neurorehabilitation conditions showed that more studies were focused on upper limbs (n=7), than on lower limbs (n=5) (369), and no studies focused on balance and walking at functional level for stroke survivors.

Although studies of VR technology include a simulated environment for exercise, exercises often lack clear instructions or feedback from the system (370,371). More recently the use of Augmented Reality (AR) systems has emerged for rehabilitation and can provide enhanced interactive environments (359,372,373). The difference between AR and VR is that the real world is used in AR as a background environment, using a head-mounted device that includes a glass window, while in VR the real environment is covered and the whole picture is completely virtual (374), Figure 2-8 shows this difference. AR add clear real-life instructions on how to perform exercises and increases engagement (359,372,373). Remarkably, AR has been shown to better enhance human behaviour when used for training for disaster management when compared to VR (374).

In physical rehabilitation, a study by Saywell et al (2021) on the Augmented Community Telerehabilitation Intervention (ACTIV) - which is a system uses telephone contacts and text messages to deliver stroke rehabilitation and limit face-to-face sessions for a 6-month period - reported no adverse events after the intervention (375). Additionally, improvement was observed in physical function (i.e., the physical subcomponent of the Stroke Impact Scale), but no difference in balance control (i.e., Step Test) and grip strength (375). The study uses augmented telerehabilitation, but the exercises were general and not tailored to individual needs and not delivered in AR environment.

A novel system of AR (the HOLOBalance system) was developed by the EU Horizon2020 scheme to provide a comprehensive, individualised tele-rehabilitation balance exercises to provide comprehensive approach to improve balance including vestibular function and cognitive training (376,377).

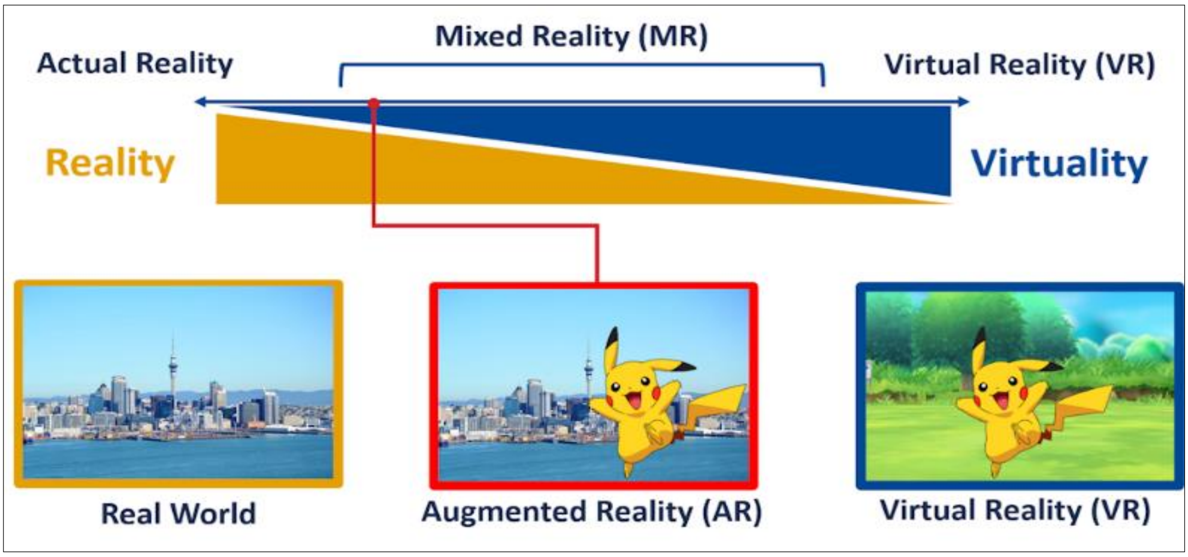


Figure 2—8 The Augmented Reality (AR) uses the real world in a background environment, in the Virtual Reality (VR) the real environment is covered and the whole picture is completely virtual (374).

2.7.1.3 The HOLOBalance system

The HOLOBalance system is a platform to set customised exercises for each patient and uses AR to present exercises and deliver instructions to the patient. The HOLOBalance platform (https://portals.rrdweb.nl/holobalance/index.phphttps://holobalance.eu/) is used to set out the exercise programme for each individual participant, which includes physical exercises based on multisensory rehabilitation, exercises for cognitive function and auditory tasks. Participants need to wear body sensors to carry signals to the system and provide the necessary feedback for exercise instructions and for safety, such as to stop the exercise if it is being performed incorrectly or the patient is at risk of falls (376). An example of a cognitive training exercise from the HOLOBalance system is illustrated in Figure 2-9, with more detail provided in Chapter 6, section “6.2.5.1.7 Cognitive training”.

Figure 2—9 An example of Augmented Reality (AR) for cognitive training (short-term memory) from the HOLOBalance system. The HOLOBalance system presents the cards of different animals, and the participant needs to choose the correct card according to the task.

In conclusion, the number of older adults at risk of falls is rising, and such falls can result in major injuries which in turn limit PA and increase deconditioning, potentially affecting social activity (64,121,378). Additionally, chronic ambulatory stroke survivors are at high risk of falls and found it difficult to return to functional life (35,57,379).

Falls occur due to inability to recover balance specially in complex situations such as turning while walking (380). Therefore, comprehensive assessment of walking at a functional level is crucial (270). In physiotherapy rehabilitation, it is important to identify patients' needs by selecting a suitable OM with a good psychometric property to assess walking at a functional level. Additionally, walking at a functional level can be affected by multiple factors, identifying these factors can improve goal setting through provide more individualised treatment goals.

Balance rehabilitation for older adults at risk of falls and for ambulatory stroke survivors usually include simple sit-to-stand or walking exercises and low adherence rates for these exercises have been documented (36,381). There is a need to address all balance components in the rehabilitation protocol, which includes training for vestibular system and cognitive function(329,382,383). Moreover, incorporating telerehabilitation can help in increasing the adherence rate to exercise.

This thesis thus aims to address some of the knowledge gaps in assessment and rehabilitation of balance and functional walking for older adults at risk of falling and in ambulatory stroke survivors.

2.8 Aims of the thesis

Therefore, the overarching aim of this thesis is to determine assessment and rehabilitation of balance and functional walking for ambulatory stroke survivors. The specific aims are to:

Study 1

I. To identify the available outcome measures used to assess walking at a functional level for ambulatory chronic stroke survivors.
II. To systematically appraise the identified OM according to the Consensus-based Standards for the selection of health status Measurement Instruments (COSMIN) risk of bias tool.

Study 2:

I. To identify the associations between walking at a functional level with a set of factors such as Subjective Visual Verticality, cognitive functions, psychosocial aspects, and physical activity levels in ambulatory chronic stroke survivors in comparison to healthy controls.

Study 3:

I. To determine the feasibility of a novel telerehabilitation (HOLOBalance) system for balance training for older adults at risk of falls.
II. To identify trends of improvements in balance and functional gait, cognitive function, and psychosocial aspects.

Study 4:

I. To determine the feasibility of a novel telerehabilitation (HOLOBalance-clinic) system for balance training for ambulatory chronic stroke survivors.
II. To identify trends of improvements in balance and functional gait, cognitive function, and psychosocial aspects.

Chapter 3: Psychometric Properties of Outcome Measures used to Assess Walking at a Functional Level in Stroke Rehabilitation. A Systematic Review.

3.1 Introduction

Mobility problems and balance dysfunction are among the most frequently reported residual disabilities after stroke and can have a major impact on stroke survivors, limiting their ability to independently perform daily activities and having a negative impact on their quality of life (38,384). Mobility problems increase the risk of falls, with about 70% of stroke survivors living at home experiencing a fall within a year post-stroke and 66% reporting a fear of falling, which is associated with loss of balance (385). To improve physiotherapy treatment for balance and regain functional walking at home and in the community, there is a need for tailored robust clinical assessment (38).

Therefore, the use of appropriate, valid, and reliable clinical outcome measures (OM) is a quality requirement in physiotherapy rehabilitation (386). Moreover, the use of standardised OM helps in comparing between studies for stroke rehabilitation, and in building high-quality, standardised "big data" sets (387,388). However, it has been reported that therapists in clinical practice find choosing an appropriate OM difficult (389). The lack of a supportive evidence-based framework has led to difficulties in choosing and comparing appropriate measures (390).

Tyson and Connell (2009) reviewed OM used for static balance in different neurological conditions (391). Six measures (the Brunel Balance Assessment (392), Berg Balance Scale (BBS) (290), Trunk Impairment Scale (393), Forward Reach, Weight Shift, and Step-Up Tests

(394)), were identified as having good psychometric properties and as being practical for use in clinical situations because of their feasibility in their application (391). These OM focus on static balance (i.e., from static positions such as sitting and standing), for people with different neurological conditions, and moderate to severe balance disorders. For persons with stroke, the BBS, OM for trunk control, sitting balance, and standing balance were reviewed (290,393,395,396). However, although these measures are commonly used, they do not test dynamic balance control, which is the ability to remain stable while performing movements or actions that require displacing or moving oneself (4).

Moreover, the OM mentioned in previous reviews did not assess walking safely in the community which requires the ability to perform functional walking, for example, walking while performing simultaneous activity like turning while walking or avoiding an obstacle such as when crossing the road (57). Assessing dynamic balance and functional walking helps to identify fall risk which increases while walking (168). The only dynamic balance test reviewed in this population is the Timed Up and Go (TUG) Test (397). The outcome of the TUG Test is a time for walking a distance of 6-metres (398), however, for optimal stroke rehabilitation there is a need to identify the difficulties in walking, not only the pace of walking.

A recent scoping review by dos Santos et al (2023) reported that the most cited tools in clinical practice guidelines for assessing balance in stroke rehabilitation were the BBS, 6-Minute Walk Test, TUG test, and 10-metre Walk Test (399). In both aforementioned reviews (397,399) no assessment tool was used to assess the methodological quality of the included studies, which in turn impacts the study’s findings. Currently, no comprehensive reviews exist of OM which assess walking at a functional level in people with stroke.

Reviews of dynamic balance and functional walking assessment measures for the stroke population are limited in number. Published reviews have focused on spatiotemporal (distance and speed) gait parameters (400), with a lack of assessment of methodological quality (401). There is a need for an up-to-date systematic review focused on dynamic balance and functional walking, including measures that can be feasibly and quickly performed in clinical practice at low or no cost.

Furthermore, walking at a functional level also requires walking while simultaneously performing additional motor or cognitive tasks. Improved dual task (DT) ability is a desirable outcome of stroke rehabilitation. DT walking requires both the ability to selectively process information in the environment (i.e., attention) and working memory while simultaneously walking (205). Recently, exercises with DT training have been shown to improve dynamic balance and walking speed and reduce the risk of falls in older adults (402), and stroke survivors (403).

A recent systematic review by Chiaramonte (2022) included 23 studies and showed that DT training promotes balance, gait, and quality of life and reduces the risk of falls more than traditional exercises for stroke survivors (403). However, the OM used in the selected studies in the Chiaramonte (2022) review were for spatiotemporal gait parameters such as the 10 - metre WT (in 21 studies), and only 2 studies added cognitive tests, with no assessment for DT walking. Another review on DT training as a treatment strategy for stroke survivors to improve balance and walking, primary used OM aimed to assess activity of daily living, and the secondary OM assessed balance and gait speed (404), however, the study did not assess DT while walking. It is important to include a DT while walking assessment in stroke rehabilitation to assess walking at a functional level and to assess motor-cognitive interference. However, there are no reviews of DT walking measures for stroke survivors.

A systematic review of contemporary OM used to assess walking at a functional level for the stroke population is now required. This review aims to identify and review psychometric properties, reliability, validity, and responsiveness (18,386,405–407) of available clinical OM for walking at a functional level which includes dynamic balance, functional walking, and DT while walking used in stroke physiotherapy rehabilitation.

3.2 Method

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (408). The PRISMA statement consists of four phases: identification from searching databases, screening related studies, checking eligibility, and including eligible studies (408). After selection of studies, the characteristics of each study are provided in the data extraction, section "3.3.2 Study characteristics and data extractions", followed by an assessment of the risk of bias of the quality of the methodological design and statistical methods in each study, section "3.3.4 Quality of methodological design" and "section 3.3.5 Quality of statistical method"; and data synthesis for psychometric properties of each OM from the included studies, section "3.3.6 Psychometric properties" (408).

3.2.1 Eligibility criteria

Studies meeting the following criteria were included: 1) adult participants aged 18 and older with stroke; 2) dynamic balance and functional walking were assessed; 3) psychometric validation studies that investigate one or more of the psychometric properties (reliability, validity, and responsiveness) of the OM; 4) The OM can be applied in clinical practice with minimum or no cost; 5) published in English with full text available.

Studies were excluded if they met the following criteria: 1) they assessed OM for sitting or standing balance, or if dynamic balance was assessed as a part of a scale that included static balance; 2) spatiotemporal gait assessment or kinetic and kinematic gait analysis were utilised; 3) no psychometric properties were evaluated; or 4) stroke survivors were included with other conditions but stroke survivors' data was not separated out from other conditions in the results section.

3.2.2 Literature search

A systematic literature search of the following databases was performed: MEDLINE, EMBASE, PsychINFO, PubMed CINAHL, Cochrane Library, AMED, Web of Science, and Scopus (from inception in 1946 up to November 2023). The search keywords for participants were stroke, for studies: assess functional walking (dynamic balance, balance in walking) and DT while walking, for outcomes: psychometric properties (reliability, validity, responsiveness). Medical Subject Headings (MeSH) terms were used and optimised by using database-specific search strategies, and the search was guided by an experienced librarian (an example of a search strategy in MEDLINE can be found in Appendix 1).

3.2.3 Study selection and data extraction

Two reviewers (KA & VA) independently reviewed all abstracts identified through the literature search and independently assessed the full-text articles of potentially relevant studies for inclusion. If a disagreement between reviewers persisted after discussion, a third reviewer (MP) was consulted.

Data extracted was as follows: outcome measures, psychometric properties tested, sample size, mean age, gender, type of stroke, time post-stroke, paretic side, walking and cognitive ability, motor recovery level, test procedure, and the measurement used for validity. Also extracted was psychometric properties data for reliability, validity, and responsiveness.

3.2.3.1 Psychometric properties terminology

Psychometric properties determine the quality of the measurement instrument; and comprise three main domains: reliability, validity, and responsiveness. The taxonomy for each property will be explained below according to the Consensus-based Standards for the selection of health status Measurement Instruments (COSMIN) criteria (8,18).

Reliability is related to the extent of stable scores of an OM to provide the same scores in repeated measurement (i.e., under several conditions) from a patient who have stable and no change in health condition. The conditions in the test-retest reliability, the time is varied; in the intra-rater reliability, the occasion is varied; and in the inter-rater reliability, the rater (assessor) is varied between measurements. The systematic and random error of a patient's score that is not related to true changes in the construct of measurement is known as Standard Error of Measurement (SEM), and the interrelation between subitems in the OM is the internal consistency of an OM (8,9).

The second psychometric property is validity and is the degree to which an instrument measures the construct it intends to measure. Validity consists of face validity which reflects whether the measure is acceptable to measure the context from the practitioners' view (10,18). Content validity is the degree to which the content adequately reflects the construct to be measured. Meanwhile, criterion validity is the degree to which the scores of an instrument are an adequate reflection of a 'gold standard' measure. A structural validity reflects the dimensionality of an instrument to evaluate the required aspects of measurement. Construct validity reflects the degree to which the score of an OM is consistent with hypotheses for OM with a similar concept (convergent validity) or opposite concept (divergent validity), or to differentiate between subgroups (such as fallers and non-fallers), or between stroke survivors and persons with no neurological conditions (known group validity) (10,18). The third psychometric property is the responsiveness is the ability of an OM to detect change over time, or between subgroups in the construct to be measured (10).

In addition to the stated psychometrics, interpretability, is an important characteristic and it adds a qualitative meaning to the quantitative scores. Interpretability of a measure can be established by the Smallest Detectable Change (MDC) or the Minimum Important Change (MIC). The MDC is the smallest change in score which can be detected beyond measurement error; when the change in MDC is larger than the measurement error (i.e., statistically significant change) the change in score can be considered as a real change. However, the MDC might be not meaningful to the patient, therefore the MIC is introduced; this is the smallest change in the score that patients perceive as important (10).

3.2.3.2 Quality assessment for an OM

The COSMIN tool was used for quality assessment (409,410). The COSMIN is a comprehensive tool consisting of a checklist to assess OM properties for OM development, content, criterion, structural, cross-cultural, and construct validities, internal consistency, reliability and measurement error, and responsiveness (409–411). Initially, to assess the risk of bias for each included study, the part in the COSMIN checklist which corresponds to the aim of the included study was completed. For example, for studies on reliability, the reliability checklist in the COSMIN tool was used.

Each COSMIN checklist for each OM property includes 2 parts. The first part determines the quality of methodological design, and the second part determines the appropriateness of statistical methods used for testing psychometric properties. More particularly, the quality of methodological design is based on specific standards for each measurement property, with an example from the reliability checklist being: “Was the time interval between the repeated measurements appropriate?”. The appropriateness of the time interval between the measurements depends on the construct of measurement and the study population. The time interval should be sufficient to ensure that patients have not changed on the construct to be measured, but also long enough to prevent recall bias (especially in intra-rater reliability). An example from the COSMIN checklist for assessing the risk of bias in a study for reliability is presented in Table 3-1.

	Very good	Adequate	Doubtful	Inadequate
Design requirement for methodological design				
Were patients stable in the interim period on the construct to be measured?				
Was the time interval between the repeated measurements appropriate?				
Were the test conditions similar for the measurements? e.g., type of administration, environment, instructions.				
Did the professional(s) administer the measurement without knowledge of scores or values of other repeated measurement(s) in the same patients?				
Statistical methods				
For continuous scores: Was an intraclass correlation coefficient (ICC) calculated?				

Table 3-1 Some questions from the Consensus-based Standards for the selection of health status Measurement Instruments (COSMIN) checklist to assess reliability.

For statistical methods quality, COSMIN recommendations were followed (24,26,30), (a summary is presented in Table 3-2). For example, the types of Intraclass Correlation Coefficient (ICC) need to be considered in assessing reliability. The one-way random effects model $ICC_{(1)}$ and the two-way random effect model $ICC_{(2)}$ are parameters for agreement and consider the systematic difference (i.e., error) in the calculation, which is preferred for generalizability. However, the two-way mixed effects model $ICC_{(3)}$ measures consistency only (7,412).

Ideally, $ICC_{(1)}$ is used if each subject is assessed by a separate set of randomly selected raters, and $ICC_{(2)}$ is used if each subject is assessed by each rater, and raters have been randomly selected. While $ICC_{(3)}$ is used in 2 possibilities 1. if each subject was assessed by each rater in the study, or 2. the raters are the only raters of interest and reliability is calculated from only a single measurement (413,414), therefore the use of $ICC_{(3)}$ does not measure the level of agreement and limits the generalizability.

Psychometric properties	Statistical method	Interpretation of correlation
Reliability Internal consistency reliability Measurement error	Cronbach's α	0.70 to 0.95
	Intraclass Correlation Coefficient (ICC)	Excellent: > 0.90 Good: between 0.9 and 0.75 Moderate: between 0.75 and 0.50 Poor: below 0.50
	Agreement Level, Standard Error of Measurement (SEM), Limit of Agreement	The variance between 2 points of reliability (e.g., time 10 seconds)
Validity Criterion validity	Factor analysis	Correlation with gold standard ≥ 0.70 or Area Under the receiver operating Curve (AUC) ≥ 0.70
Construct validity	Pearson's correlation (*r*) or Spearman's correlation(r_s)	Hypothesis testing for correlation with a test assessing the same construct ≥ 0.50 for appropriate correlation
Known-group validity	Cut-off score or sensitivity, and specificity	
Responsiveness Floor and ceiling effect	Correlations, or AUC, or sensitivity, and specificity	AUC ≥70 Effect Size Standard Response Means ≤ 15% of the total score

Table 3-2 Statistical method and outcomes for good measurement properties (407,409,412,413), alpha (α), Area Under the receiver operating Curve (AUC), Intraclass Correlation Coefficient (ICC), Standard Error of Measurement (SEM), Pearson's correlation (r) or Spearman's correlation(r_s).

To rate the methodological design and statistical methods quality for each psychometric property, the worst-score-count method was applied in a 4-point scale comprising of very good (++), adequate (+), doubtful (0), and inadequate (-) (409,410). After determining the quality of methodological design and statistical methods for each selected study, the psychometric properties for each OM were summarised (i.e., the ten boxes for psychometric properties) (8). Two independent reviewers (KA & VA) performed the quality assessment for methodological design and SM. The level of agreement between the two reviewers was determined as a percentage. If disagreement persisted after the discussion, a third reviewer (MP) was consulted.

For data synthesis, included studies were first grouped into categories according to the level of OM task difficulty and the capacity required to complete these tasks. Consequently, the OM were classified into three categories, to assess: dynamic balance, functional walking, and DT walking. Then for each OM, reported psychometric properties (i.e., validity, reliability, and responsiveness) were collated. After assessing the risk of bias in each study, the overall quality summary for each OM from the included studies was obtained. If more than one study investigated the same psychometric property of the same OM, then the study with the highest quality of methodological design and the statistical outcomes from this study (i.e., which had the highest quality methodological design) were added to the overall quality table (10). No meta-analysis was carried out due to the lack of homogeneity and thus a narrative of the findings is presented.

3.3 Results

3.3.1 Study selection

A total of 9337 studies were identified from the literature search and 7072 studies remained after duplicate removal. During the abstract screening, 6527 studies were excluded, leaving 545 for full-text assessment. After a thorough assessment for eligibility, 491 studies were excluded (326 studies were not related to dynamic balance, balance in walking, and DT while walking, 67 studies not applicable for clinical practice, 87 studies did not assess any psychometric properties, and 11 studies contained results where stroke subjects were not separated from the results of all included conditions), 54 studies were included in this systematic review, the search results are presented Figure 3-1.

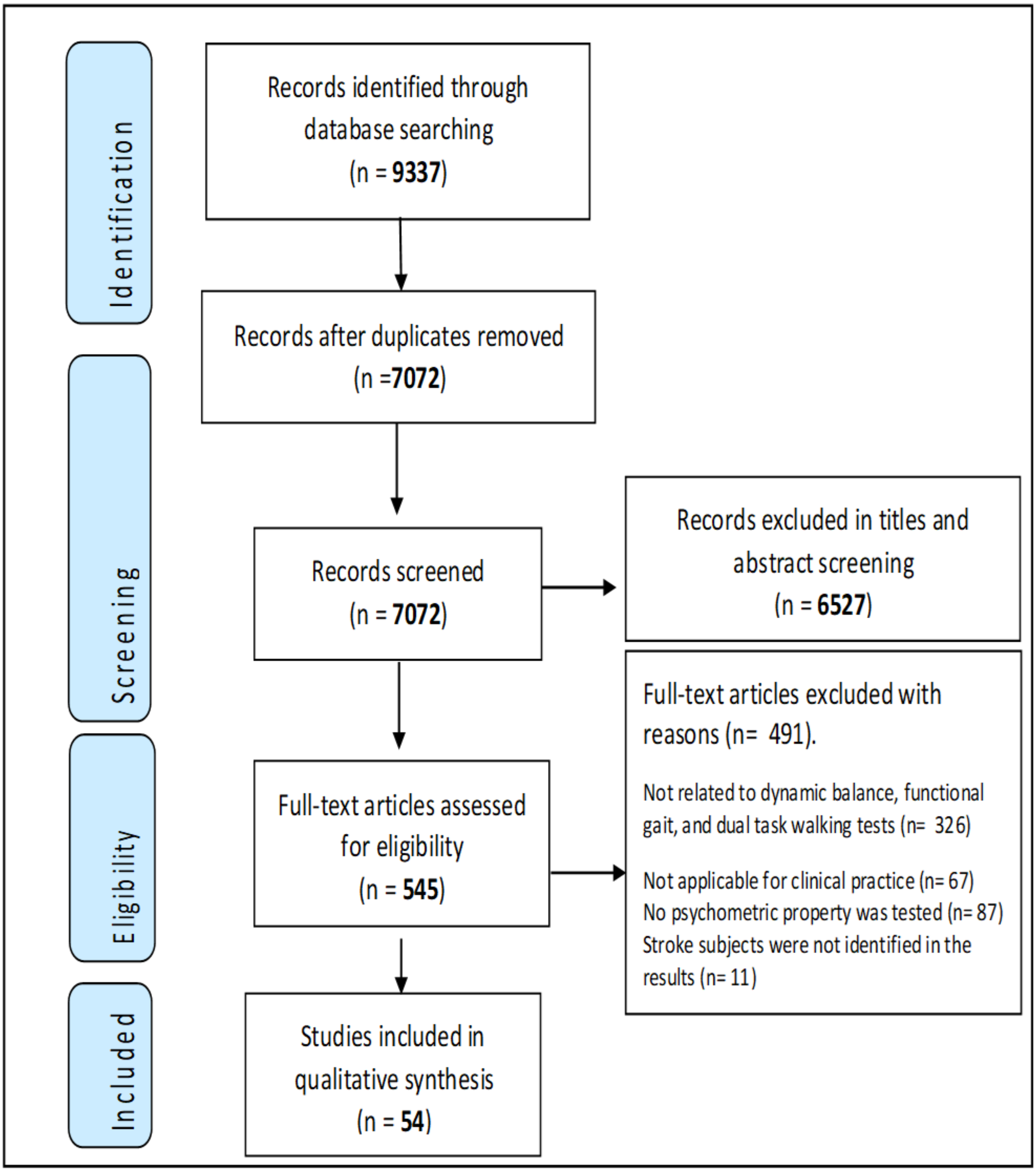


Figure 3—1 Flow diagram outlining selection process according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses).

3.3.2 Study characteristics and data extractions

The total number of participants from all included studies was 3196 stroke survivors. Time post-stroke was less than 6 months in 13 studies (291,415,424–427,416–423) and more than 6 months in 33 (293,294,434–443,297,444–453,422,454–456,428–433). Type of stroke suffered by participants was recorded in 33 studies (291,294,423–431,433,297,435,439,442,443,447,448,451,453,454,456,415,457–460,416,417,419–422) where 80% were ischemic, and 20% haemorrhagic. The paretic side was recorded in 43 studies (291,293,423–432,294,433–435,437–443,297,447,448,450,451,453–455,457,459,460,415,461–463,416,419–422), and 47% of participants had the right paretic side. Motor recovery was measured by Fugl-Meyer assessment in 13 studies (415,416,442,447,450,418,427,431,433,436–438,441); Barthel Index in 7 studies (297,415–417,421,423,440). The Chedoke McMaster Stroke Assessment was used in 5 studies (294,430,449,457,458); and the Functional Ambulation Category was used in two studies (417,419).

Motor recovery was also measured by BBS in two studies (448,459) and by Functional Independence Measure (457), Brunnstrom stages of recovery (424), Stroke Rehabilitation Assessment of Movement (293), Rivermead Mobility Index (417), and Clinical Balance & Mobility Scale (458) in one study for each measure. The level of walking ability was mentioned in 41 studies (291,293,434–439,443–446,418,447–456,421,458,459,463,422,424,428–431).

Cognitive ability was measured using the Montreal Cognitive Assessment (MOCA) in 4 studies (422,430,433,449), Mini-Mental State Examination in 12 studies (415,416,460,462,417,426–

428,431,432,442,448), and Abbreviated Mental Test in 13 studies (294,418,454–456,436–439,447,450,452,453).

Thirty-five studies investigated OM reliability (291,294,428–430,432–435,437–439,297,440,443–451,415,452,456,460,461,463,417–419,422,423,427). The time interval ranged from 15 minutes (433) to 14 days (430,448) for test-retest reliability and one month for intra-rater reliability (417). In inter-rater reliability the scoring of OM by at least 2 assessors was simultaneously in all studies except in one, the scoring was after 4 weeks of testing (446). Forty-two studies investigated OM validity (293,294,425,427–435,297,436–443,445,446,415,447,449,451,452,456–458,460–462,417,463,464,419,421–424). The BBS has been used for correlation in hypothetical testing for construct validity in 27 studies (293,294,431–434,437–441,443,415,448,450,452,456,457,460,461,417–419,421,424,426,427). Twelve studies assessed OM responsiveness (297,416,458,459,418,420,423,426,427,433,443,457), the extracted data are presented in Table 3-3.

The test	Author, year	Psychometric property tested	Sample size (n)	Mean age (SD)	Male/ female (N)	Type of stoke	Time post stroke (Mean or as indicated)	Paretic side RT/LT	Specific selection criteria	Cognitive ability (Mean or as indicated)	Motor recovery (Mean or as indicated)	Test procedure	Time required for testing	Time interval between tests for reliability	Measurement used in correlation for validity	Assessors
Dynamic balance tests																
BESTest	(Rodrigues al, 2014)	Reliability Validity	16 S	61.1 (7.5)	13/3	_	54.5 months	3/13	_	Mini-Mental State Examination was 27	_	36 items classified in 6 subgroups. Each item is scored on a 4-level scale. Max. score is 108 points.	45 min	7 days	-BBS -ABC scale	1 assessor
	(Sahin et al, 2019)	Validity	50 S Faller 26 S Non-fallers 24 S	53.33 (18.9) 64.03 (14.6)	12/14 18/6	_	30 33 months	15/11 17/7	Able to walk with or without assistive device	_	mRS 3 STREAM 47				-BBS -ABC scale -Postural and limit of stability by Biodex Balance System	1 assessor
	(Rudolf et al, 2020)	Responsiveness	88 S	56	56/32	I 69 H 19	4 months	38/48 B 2	_	Mini-Mental State Examination was 28	FIM				-BBS -FAC -FGA	1 assessor
	(Chinsongkram et al, 2014)	Reliability Validity	70 S 12 S 67 S	57.01 (12.2)	38/32	I 54 H 16	1.11 months	39/31	_	Mini-Mental State Examination was 28	FMA-M 55.53 BI 61.93			7 days	-BESTest -BBS -PASS -CB&M scale	5 PTs
	(Chinsongkram et al, 2016)	Responsiveness	49 S	57.79 (11.7)	29/20	I 36 H 13	38.69 days	27/22	_	Mini-Mental State Examination was 28	FMA-M 38 BI 50				_	1 assessor
Mini-BESTest	(Tsang et al, 2013)	Reliability Validity	106 S 106 S 48 HC	57.1 (11) 57.1 (11) 60.2	73/33 73/33 28/20	I 56 H 46 U 4	Median 2.9 years	60/46	-	Abbreviated Mental Test median was 10.	CMS MAS	14 items focusing on dynamic balance.	15 min	10 days	-BBS -TUG test - One Leg Standing - Functional reach test	2 assessors

				(9.3)						Geriatric Depression Scale-Short Form median was 5		The score for each item ranges from 0 -2 Max. score is 28 points			-ABC scale - Oxford Community Stroke Project Classification	
	(Madhavan& Bishnoi, 2017)	Validity	41 S	59.4 (9)	31/10	I 35 H 6	5.68 years	21/20	Able to walk with or without aids for 5 min	Mini-Mental State Examination was 28.43	FMA-LE-M 51				-BBS -10mWT	1 assessor
	(Miyata et al, 2020)	Validity	88 S	71 (9.2)	56/32	I 61 H 27	60.3 days	43/45	Able to walk with no help	HDS-R >21	BRS-LE III 2 IV 5 V 45 VI 36				-BBS -Comfortable Walking Speed Test	1 assessor
Brief-BESTest	(Huang & Pang, 2016)	Reliability Validity Floor and ceiling effect	27 S 50 S 27 HC	59.2 (7.3) 56.7 (7.7)	32/18 11/16	I 30 H 20	9 years	25/25	_	-Geriatric Depression Scale-Short Form 3.5 -Montreal Cognitive Assessment was 25	FMA-LE Median 19	8 items scored from 0-3 for each item. Maximum score is 24.	7 min	15 minutes	-BBS -PASS	1 assessor
S-BESTest Brief-BESTest Mini-BESTest	(Winairuk et al, 2019)	Reliability Validity Responsiveness	12 S 70 S	58.42 (13.4) 55.24 (12.1)	8/4 44/26	_ I 64 H 6	40.60 days 15.81 days	_ 37/33	_	Mini-Mental State Examination 27.33	FMA-LE 19.39	As above	10 min	7 days	-BESTest -BBS	5 PTs
BESTest, Mini-BESTest, Brief BESTest	(Hasegawa et al, 2021)	Responsiveness	30 S	76.4 (10.4)	17/13	I 30	24 days	19/11	_	_	FIM 78.2	As above			-BBS	3 PTs
Mini-BESTest, Short BESTest	(Miyata et al, 2022)	Validity Internal consistency	115 S	70.8 (11.2)	78/37	I 77 H 38	62.3 days	60/55	Able to stand	_	_	As above			-BESTest	5 PTs

Community balance and mobility scale	(Knorr et al, 2010)	Validity Sensitivity to change Floor and ceiling effect	44 S	62.6 (12.6)	24/20	I 41 H 3	98.6 days	16/28	_	FIM-Cog 33	CMSA leg 6 CMSA foot 5 FIM 114	19 items - each item is scored from 0 to 5 based on time, distance, and quality of performance. Max. score is 96	_		-BBS -TUG test	1 assessor
	(Miller et al, 2016)	Validity Responsiveness	100 S	62.8 (12.5)	57/43	I 79 H 18 U 3	3.5 months	_	Ambulatory	Able to follow instructions	CMSA Leg, foot 5. CLBMS 3				_	1 assessor
Four-square step test	(Goh et al, 2013)	Reliability Validity	15 S 15 HC	57.70 (8.2) 57.30 (3.6)	11/4 2/13	_	5.60 years	7/8	Able to walk 10m independently with or without an aid	_	_	Starting position is in square 1 facing square 2. Step forward, to right, backward, and to left into each quadrant in both directions. Time was recorded	_	Not provided	-BBS -LOS -TUG test	2 assessors
Functional gait tests																
The L-shape walking test	(Kim et al, 2015)	Reliability Validity	33 S	52.4 (11.2)	20/13	I 15 H 18	29.1 months	17/16	Able to walk 20m independently with or without an aid	Able to follow instructions	_	Stand, walk in a straight line for 3m, turn, walk for 7m, turn around, walk back 7m, turn, walk 3m to the chair, and sit. Time was recorded	_	One hour	-TUG -10mWT -2-minute walk test	1 assessor
The L-shape walking test for assessing turning ability	(Ng et al, 2023)	Reliability Validity Cut-off time	30 S 32 HC	58 (5)	19/11	I 18 H 9 Other 3	7.8 (4.8) years	21/9	Able to walk independently without aid	Abbreviated Mental Test ≥ 7	FMA-LE	Stand, walk 3 m and turn 90°, walk another 7 m, turn 180°, then walk back to the chair, and sit. Time and turning direction were recorded	_	Not provided	- FMA - Handgrip - strength test - FTSTS test - BBS - TUG Test - Short-Form Health Survey - CIMQ	1 assessor

180° turn test	(Robinson & Ng, 2018)	Reliability Cut-off time	33 S 32 HC	60.18 (6.4) 61.84 (4.6)	22/11 10/22	_	112.21 days	_	Able to walk 10m with or without an aid	Abbreviated Mental Test ≥ 7	FMA-LE 23.8	Stand then turn 180° on the spot from a standing start position as fast as they can. Time and number of steps were recorded.	_	7–10 days	- FMA - Ankle planter flexion - FTSTS test - BBS - TUG test	2 assessors
Parallel Walk Test	(Ng et al, 2015)	Validity	37 S 35 HC	62 (6.2) 64.3 (7.8)	26/11 11/24	_	7.8 years	_	Able to walk 10m with or without an aid	Abbreviated Mental Test > 7	FMA-LE 25.9	Walk at comfortable walking speed for 6m between 3 sets of parallel lines. Time and accuracy of foot placement recorded.	_		-LOS -LL muscle strength	1 assessor
Sideways Walk Test	(Ng et al, 2016)	Reliability Validity	29 S 32 HC	60 (6.3) 61.8 (4.6)	18/11 10/22	_	9.2 years	20/9	Able to walk 10m independently with or without assistive device	Abbreviated Mental Test mean 9.4	FMA-LE 24.06	Walk sideways along the 5m walkway at self-selected speed. Time and step count recorded.	_	7–10 days	-LL muscle strength -FTSTS test -BBS -TUG test -ABC scale -CIMQ	1 assessor
Walking Obstacle Course Test	(Ng et al, 2017)	Reliability Validity	29 S 32 HC	57.9 (5.5) 63.6 (5.6)	18/11 10/20	_	7.9 years	21/8	Can do the test independently	Abbreviated Mental Test ≥ 7	FMA-LE 22.14	1. Normal walking 2. Walking with a tray 3. Walking with dark glasses.	_	7–10 days	-FTSTS test -BBS -TUG test -CIMQ	1 assessor
The Long-Distance Corridor Walk Test	(Ng et al, 2020)	Reliability Validity	25 S 25 HC	60.6 (5.3) 64.3 (6.7)	9/16 19/6	I 18 H 7	3.34 years	13/12	Able to walk 10m without an assistive device	Abbreviated Mental Test ≥ 7	_	Walk back and forth along a 20m corridor. The time and steps taken in the first 20m and the distance covered over 2min are recorded.	_	7 days	-FMA-LE -LL muscle strength -BBS -TUG test -Limit of stability -Narrow-Corridor Walk Test -CIMQ	1 assessor

The figure of eight walk test	(Wong et al, 2013)	Reliability Validity	35 S 29 HC	57.26 (7.1) 57.76 (5.7)	27/8 19/10	_	At least 1 year	24/11	Able to walk 10m with or without an assistive device	Abbreviated Mental Test ≥ 7	FMA-LE 26.6	Stand between two cones, walk at usual pace in a figure of 8 walking path, stop upon returning to the starting position. Time was recorded.	_	7 days	-FMA-LE -LL muscle strength -FTSTS test -BBS -TUG test -10m WT -ABC scale	2 assessors
The cone evasion walk test	(Sjoholm et al, 2019)	Reliability Validity	20 S 221 S	74 (NA) 73 (NA)	13/7 127/ 94	I 14 H 3 U 3 I 153 H 18 U 44 B 6	Median 5 days	4/13 Non 3 17/30 Non 162 B 11	walk with or without an aid	-Star cancellation test -Montreal Cognitive Assessment	_	Walk twice in usual speed for 3m between four cones without touching them.	_	Not provided	-FAC -TUG test -TUG-cog -The rate of falls in 6 months follow up	10 PTs
Six -Spot Step Test	(Lindvall et al, 2021)	Reliability Validity	81 S	70 (7.9)	47/34	I 60 H 21	4.8 years	46/35	Able to walk 10m	Able to understand verbal and written information	NIHSS for arm and leg.	Walk fast along 5x1 m walkway, with cones placed in the way. Time and number of shoving the block were recorded.	_		-DGI -FSST -TUG test -Sit to Stand -ABC scale	5 PTs
	(Liu et al, 2021)	Reliability Validity	25 S 25 S 25 HC	60.6 (5.4)	19/6	-	3.33 years	-	walk independently 10m	Abbreviated Mental Test ≥7	FMA-LE 29.3	As above	_		-BBS -FMA -LOS -TUG test -dynamometer -Community integration measure	2 assessors
3-m Backward Walk Test	(Kocaman et al, 2021)	Reliability Validity	41 S	59 Median	28/13	I 19 H 22	_	17/24	-	Mini-Mental State Examination > 24	_	Walk 3m backward. Time was recorded.	_		-BBS -TUG test	1 assessor

	(Demark et al, 2022)	Reliability Subacute stroke Chronic stroke Validity Subacute stroke Chronic stroke	28 S 25 S 34 S 29 S	61 (13) 56 (11) 60 (12) 57 (12)	17/11 18/7 21/13 20/9	_	Subacute< 8 months Chronic> 8 months	16/12 13/12 20/14 14/15	Able to walk 10 feet. Able to step backward with the affected leg.	_	_	Walk 3m backward. Time was recorded.	_		GAITRite	1 assessor
Timed Up and Go (TUG) Test	(Nair et al, 1999)	Validity	33 S	68.2 Median	22/11	_	_	15/15 B 3	_	Mini-Mental State Examination > 24	BI 94	Stand from a chair, walk 3m, turn around, return to the chair, and sit down. Time was recorded.	_		BI	1 OT
	(Ng & Hui-Chan, 2005)	Reliability (Test-retest) Validity	11 S 10 HC	61.1 (6.8) 63.5 (6.1)	6/5 5/5	I 5 H 6	5.6 years	5/6	Able to walk 10m with or without aid	Abbreviated Mental Test ≥ 7	_		_	7 days	6min WT GAITRite Composite Spasticity Scale	2 assessors
	(Persson et al, 2014)	Responsiveness	91S	72.6 (NA)	53/38	I 82 H 9	From 14 days	48/43	Able to walk	_	BBS 41	Stand from a chair, walk 3m at their max. speed, turn, walk and sit back down. Time was recorded.	_		MAS	PT
	(Johansen et al, 2016)	Reliability (Intra-rater Inter-rater)	62 S	71.6 (13.6)	41/21	I 54 H 6 U 2	median 5 days	29/22 Non 11	Able to walk	_	_	Stand, walk 3m, turn, walk back, and sit back down. No physical assistance was given. The use of an assistive device was recorded.	_	One hour	30sec stand test New Mobility Score	2 PTs
	(Alghadir et al, 2018)	Reliability Validity Responsiveness	56 S	58.6 (9.8)	39/17	I 32 H 24	22.2 months	33/23	Able to walk 10m with or without an aid	_	_	TUG test	_		BBS DGI	PT

	(Faria et al, 2012)	Reliability	48 S 48 HC	59.12 (2.28)	24/24	_	39.7 months	_	Able to perform TUG test with or without an aid	_	_	Walk along 10-m walkway and turn in with the preference side. Time was recorded.	_		Video recording	PT
	(Faria et al, 2013) a	Development Reliability Validity	22 S 13 S	54.7 (15.4) 63.4 (13.1)	12/10 6/7	_	52.2 months 79.9 months	_	Able to perform TUG test with or without device.	_	_	24 items, 5 related to sit-to-stand, 8 to gait, 5 to turning, and 6 to stand-to-sit.	_		Variable of TUG-ABS were determined. Video recording	8 PTs
	(Faria et al, 2013) b	Reliability Validity	48 S 48 HC	59.3 (15.8) 59.1 (15.8)	24/24 24/24	_	51.3 months	_	Able to perform TUG test with or without device.	_	_	Stand, walk at a self-selected speed over 3m, turn, walk back, and sit down.	_		Video recording A questionnaire for PTs	2 PTs
	(Chan et al, 2017)	Reliability Validity	33 S 32 HC	60.18 (6.41) 61.84 (4.59)	22/11 10/22	I 15 H 11 Others 7	9.35 years	24/9	Able to walk 10m with or without aid	Abbreviated Mental Test was 9	FMA-LE 23.80	Stand, walk 3m turn around a cone towards the paretic side, walk back and sit, while carrying a glass of water. Time and number of steps were recorded.	_		TUG test FTSTS test BBS ABC scale CIMQ	2 assessors
TUG obstacle cross test	(Ng et al, 2023)	Reliability Validity	28 S 30 HC	61.82 (6.27)	11/17	_	3.57 Years	18/10	Able to walk independently for at least 10m, with or without an assistive device	Abbreviated Mental Test score ≥7	_	Stand, walk forward for 5m, as fast as they can, step over obstacles, turn180degrees, step over the obstacle again, then walk back and sit down	_	7 days	FMA Isometric muscle strength BBS TUG test Narrow-Corridor Walk Test	2 assessors
Timed 360° Turn Test	(Shiu et al, 2016)	Reliability Validity	72 S 35 HC	62 (6.24)	11/24	I 26 H 11	7.8 (3) years	17/20	Able to walk 10m with or without aids	Abbreviated Mental Test score ≥7	_	Stand with arms by side and feet apart. Timing was started from the word “go” and	_	7-10 days	FMA Ankle muscle strength BBS Limit of Stability test	2 assessors

												stopped when subject's shoulders were facing forward again			FTSTS test 10-m walk test TUG test	
Loaded and Unloaded Timed Stair Test	(Ng et al, 2023)	Reliability Validity	94 S 34 HC	63.17 (6.19)	53/41	I 66 H 28	80.87 (53.68) months	56/38	Able to climb the stairs	Abbreviated Mental Test score ≥7	_	Stand, walk 3m, ascend a staircase, turn, descend a staircase, walk 3m, turn, and sit. Time for completion was recorded.	_	15 min	FMA BBS Limit of Stability TUG test	One Assessor
The shuttle walk test	(Van Bloemendaal et al, 2012)	Reliability Validity	75 S	58.8 (9.8)	47/28	I 57 H 18	24.7 months	43/32	Able to walk without physical assistance	Able to follow instructions	_	23 stages, each last for 1min speed is increased by 0.25km/h the beginning and end of each stage are indicated by an auditory signal.	_		6min WT	2 PT
Emory Functional Ambulation Profile	(Wolf et al, 1999)	Reliability Validity	28 S 28 HC	56.04 (13.8) 56.43 (12.8)	_	_	13.59 months	15/13	Able to walk 10m. Ascend and descend 5 stairs	Able to follow commands	_	5 walking tasks on a 5m walkway on different terrains.	_		BBS Functional reach test 10mWT	4 assessors
	(Baer & Wolf, 2001)	Reliability Validity	26 S	54.5 (12.7)	13/13	I 20 H 6	32.2 days	Rt 18 Lt 4 B 4	_	Able to follow commands		Time was recorded, as was the use of an assistive device.	_		BBS FIM FAM	2 assessors
	(Liaw et al, 2006)	Reliability Validity Responsiveness	40 S	57.45 (10.9)	33/7	I 25 H 15	Median 33 days	19/21	Able to walk with one person's help	Able to follow commands	FAC 2	Modified E-FAP. The same test procedure. The process of scoring is modified.	_		10mWT BI RMI	PT
The dynamic gait index	(Jonsdottir & Cattane, 2007)	Reliability Validity	25 S	61.6 (13.1)	18/7	_	4.2 years	9/14	Able to walk 10 m with or without an aid	Able to follow commands	BI 95.6	8 items based on walking ability score on a 4-point scale. Max score is 24	_		BBS TUG ABC scale	2 assessors

	(Vistamehr et, 2016)	Validity	19 S	62 (11)	13/6	_	24 months	5/14	Able to walk 10m with no or at least one-person assistant	_	FMA-LE 24.3	Walk on a split-belt instrumented treadmill at a self-selected speed	_		BBS Margins of stability Angular momentum	1 assessor
	(An et al, 2017)	Validity of the original and short versions	57 S	52 (15.4)	32/25	I 39 H 8	9.04 months	27/30	Able to walk 10m without an aid	Mini-Mental State Examination >24.	FMA-LE 22	4 -item (short) version of the DGI	_		Sit to stand test POMA 10m walk test FMA TIS	2 PTs
	Modified DGI (Matsuda et al, 2014)	Validity	239 S	64.3 (15.3)	141/98	_	_	_	Able to walk 6m with or without assistive device	_	_	Original 8-item DGI used with modification: Decrease in distance, scoring on a 3-point scale.	_		_	PT
Functional Gait Assessment (FGA)	(Van Bloemendaal et al, 2019)	Validity	52 S	62 (12)	32/20	I 39 H 13	Median 6 weeks	27/25	Able to walk without physical assistive device	Able to follow commands	BI 20	10 tasks assessing walking balance on a 6m walkway. Each item scored from 0-3. Max. score 30.	10-15 min		FAC BBS SIS- Mobility 10mWT 6min WT	1 assessor
	(Lin et al, 2010)	Reliability Validity Responsiveness	48 S 45 S	54.9 (10.2)60 (12.6)	28/2125/20	I 27 H 21 I 30 H 15	Median 9 months	24/21 21/28	Walk for 10m with or without a device	Able to follow commands	BI 18				DGI 4-item DGI 10m walk test BI PASS	PT
	(Thieme et al, 2009)	Reliability Validity	28 S	69.6 (9.5)	16/12	I 23 H 5	50.5 days	_	Walk with or without an aid for 15m	Mini-Mental State Examination 27	FAC 4.04 BI 86.43 RMI 10.75				BBS Fast walking speed	1 assessor

Dual task walking tests																
Dual task walking tests	(Chan & Tsang, 2017)	Reliability	59 S 45 HC	62.4 (6.8) 61.3 (4.8)	29/30 9/36	I 40 H 17 U 2	5.4 years	25/34	Able to walk independently 15m	Mini-Mental State Examination 28	BBS 55.9	1 physical task, 1 cognitive task and a combination of two tasks.	_		TUG test BBS	2 assessors
	(Yang et al, 2016)	Reliability Validity	88 S	62.2 (7.8)	64/24	_	105.9 months	_	Able to walk with or without aids	-Montreal Cognitive Assessment 24.8 -Geriatric Depression Scale-Short Form 4	CMSA-M (Chedoke McMaster Stroke Assessment Motor) leg 5 CMSA-M foot 4	14-item 1) Walk in self-selected and maximum speed; across obstacle; backward walking; TUG test.2) with cognitive task. 3) with manual task.	_		ABC scale	2 assessors
	(Tsang et al, 2019)	Reliability Validity	30 S	62.4 (6.7)	22/8	I 19 H 9 U 2	9.2 years	Rt 16 Lt 13 Both 1	Able to walk independently for 1 minute	Montreal Cognitive Assessment 27	CMSA leg, foot 8.8	2 walking tasks (1min level-ground walking with and without obstacle-negotiation) with 8 cognitive tasks.	_		Walking distance, obstacle hitting rate NCR Reaction time	2 assessors

Table 3-3 Data Extraction Tables. Both type of stroke (B). Berg Balance Scale (BBS). Barthel Index (BI). Brunnstrom Recovery Stages lower extremity (BRS-LE). Community Balance and Mobility scale (CB&M) scale. Community Integration Measure Questionnaires (CIMQ). Chedoke-McMaster Stroke Assessment (CMSA). Chedoke-McMaster Stroke Assessment- Motor (CMSA-M). Clinical Balance & Mobility Scale (CLBMS). Dynamic Gait Index (DGI). Functional Ambulation Category (FAC). Functional Assessment Measure (FAM). Functional Independence Measure (FIM). Functional Independence Measure-Motor (FIM-M). Functional Independence Measure-Lower Extremity (FIM-LE). Functional Independence Measure- Cognitive (FIM-Cog). Fugl-Myer assessment (FMA). Fugl-Myer Assessment Motor (FMA-M), Fugl-Meyer Assessment Motor Lower Extremity (FM-M-LE). Four Square Step Test (FSST). Haemorrhagic stroke (H). Healthy Control (HC). Hasegawa Dementia Scale-Revised (HDS-R). Ischemic stroke (I). metre (m). minutes (min). Lower limb (LL). Limit of Stability (LOS). Motor Assessment Scale (MAS). modified Rankin Scale (mRS). Number of Correct Responses (NCR). National Institutes of Health Stroke Scale (NIHSS). Occupational Therapist (OT). Postural Assessment Scale for Stroke patients (PASS). Performance-Oriented Mobility Assessment (POMA). Physiotherapist (PT). Rivermead Mobility Index (RMI). Stroke Impairment Assessment Set (SIAS). Stroke Impact Scale (SIS). Stroke Rehabilitation Assessment of Movement (STREAM). Timed Up and Go Test (TUG test). TUG Assessment of Biomechanical Strategies (TUG-ABS). Timed Up and Go Test cognitive (TUG-cog). Trunk Impairment Scale (TIS). Unknown (U). Five-Times-Sit-to-Stand Test (5-TSTST). 6 minutes' Walk Test (6min WT). 10-metre Walk Test (10mWT). (_) was not indicated.

3.3.3 Identified outcome measures

From the 54 included studies, a total of 30 different OM was identified. Fifteen studies evaluated 6 dynamic balance OM, 36 studies evaluated 21 functional walking OM and 3 studies evaluated DT while walking OM. The identified OM were classified into the following three categories:

Category one: Dynamic balance OM included the Balance Evaluation System Test (BESTest) (293,415,416,420,426,432), and the BESTest short forms (Mini-BESTest) (294,424–426,431), Brief BESTest (433), Short BESTest (427), Community Balance and Mobility scale (457,458), and Four-Square Step Test (434).

Category two: OM to assess functional ~~gait~~ walking and further classified to groups A and B as follows.

A) Sixteen tests assessing functional walking task: L-Shape Walk Test (429), Turning in L-Shape Walk Test (453), Parallel Walk Test (436), Sideways Walk Test (437), Standardised Walking Obstacle Course Test (438), Long-Distance Corridor Walk Test (439), Timed 180° Turn Test (418), Cone Evasion Test (422), Figure-of-Eight Walk Test (450), Six-Spot-Step Test (451,452), 3-metre Backward Walk Test (460,463). In addition to the TUG test (291,397,428,443,444,459,462), are the TUG test with a motor task (447), the Timed-Up and Go Assessment of Biomechanical Strategies (TUG-ABS) (445,446), the Timed-Up and Go with Obstacle Cross Test (455), Timed 360° Turn Test (456) and Loaded and Unloaded Stair Test (454).

B) Four tests assessing complex walking tasks: the Shuttle Walk Test (435), Emory Functional Ambulation Test (419,423,461), Dynamic Gait Index (DGI) (440–442,464), and Functional Gait Assessment (FGA) (297,417,421).

Category three: DT while walking OM included a walk and turn with auditory test (448), walking tests (at self-selected and maximum speed, obstacle crossing, backward walking, and TUG) with a concurrent manual (449), or cognitive task (verbal fluency, serial subtractions, category naming, and shopping list recall) (430).

3.3.4 Quality of methodological design

High agreement (96%) was found between both reviewers for methodological design assessment and moderate agreement (86%) for the appropriateness of the quality of statistical methods used. Disagreement between reviewers was found for one item, statistical correlation for validity, and this was resolved with discussion, and in consulting a third reviewer for 6 studies (426,431,465,466). All COSMIN checklist criteria for assessing the psychometric properties of OM were applicable to the included studies. A summary of the quality assessment of the methodological design is presented in Table 4. The following sections will present the quality of methodological design for reliability, validity, and responsiveness in each OM category. (Appendix 2 presents the quality assessment tables for the included studies in the Systematic Review).

3.3.4.1 Category 1: dynamic balance OM

3.3.4.1.1 Reliability

Both intra-rater and inter-rater reliability have been reported for all dynamic balance OM except the Community Balance and Mobility scale. The methodological design for intra-rater reliability was doubtful or inadequate for all OM, however, the inter-rater reliability methodological design was very good for the Brief BESTest (433), and Mini-BESTest (294), good in BESTest (432) and Four Step Square Test (434), and inadequate in the Short BESTest (427). Test-retest reliability has not yet been investigated for OM in the dynamic balance category. Internal consistency has been investigated for BESTest (415) and its short forms, and the methodological design was very good for the Mini-BESTest and Short BESTest (425) only. The results are presented in Table 3-4.

3.3.4.1.2 Validity

Even though hypothesis testing for construct validity has been established for all OM in the dynamic balance category and known group validity was determined for BESTest and Four-Square Step Test; criterion validity was determined only for the Mini-, Brief-, and Short-BESTest. Structural validity was tested for the Community Balance and Mobility scale only, and content validity was not determined for any dynamic balance OM. Studies on the construct and known-group validities for the BESTest (293,415,432), Mini-BESTest (294,424,431), and Brief-BESTest (433) had a very good methodological design. For the Community Balance and Mobility scale, the known-group validity methodological design was very good (457), however, the structural validity methodological design was adequate (458). The construct validity methodological design for the Four-Square Step Test (434) was very good. The results are presented in Table 3-4.

3.3.4.1.3 Responsiveness

Responsiveness was identified for the BESTest, Mini-, Brief-, and Short-BESTest, as well as for the Community Balance and Mobility scale. The methodological design was very good for the BESTest, Mini-BESTest (416,426) and the Community Balance and Mobility scale (457), and adequate for the Brief BESTest (420), the results are presented in Table 3-4.

3.3.4.2 Category 2: functional walking OM

3.3.4.2.1 Reliability

For all types of reliability, no methodological design was rated very good according to the COSMIN criteria. The methodological design for test-retest reliability was adequate for ten OM in group (A): Parallel, Sideways, Standardised Walking Obstacle Course, Long-Distance Corridor, Timed 180° Turn, Figure-of-Eight, Six-Spot Step, TUG test, and Timed 360° Turn (418,428,462,436–439,450,451,455,456) and was rated as doubtful for the 3-metre Backward Walk test (460). In contrast, intra-rater reliability methodological design was adequate in 3 OM: Six-Spot Step test (451), Timed 360° Turn (456), Loaded and Unloaded Timed Stair Test (454), doubtful for 8 OM (418,429,436,447,450,451,453,463) and was rated as inadequate for two OM (422,437). Inter-rater reliability methodological design was adequate for 11 OM (418,429,456,436–439,450–452,455) but doubtful for 2 OM (422,463). The results are presented in Table 3-4.

In the functional walking (complex tasks) group (B), the test-retest reliability methodological design was adequate for all OM (297,419,421,423,435,440), except for the modified-DGI (464). Intra-rater reliability was tested for FGA (421) only, and the methodological design was adequate. The inter-rater reliability methodological design was adequate for the FGA (421), Emory Functional Ambulation (423,461), and DGI (440). The results are presented in Table 3-4.

3.3.4.2.2 Validity

Hypothesis testing for construct validity methodological design was very good for all functional ~~gait~~ walking OM (297,417,437–439,450,451,453–455,460,461,418,419,421,423,428,429,435,436). The known-group validity methodological design was very good for the Six-Spot Step Test (452), DGI (442), Turning in L-Shape Walk Test (453), and Loaded and Unloaded Timed Stair Test (454) but inadequate for the TUG test (428). The content validity methodological design for TUG-ABS was doubtful (445), but its known group validity was very good (446). The results are presented in Table 3-4. The other types of validity were not assessed.

3.3.4.2.3 Responsiveness

The methodological design was very good for DGI (297) and FGA (297) and adequate for Emory Functional Ambulation (423) and TUG tests (459), and was not investigated for the other functional walking OM, the results are presented in Table 3-4.

3.3.4.3 Category 3: DT while walking OM

For all OM in this category, methodological design for test-retest reliability was adequate (448,449), but was very good for construct and known-group validities (430,449), The results are presented in Table 3-4. Other types of reliability, validity, and responsiveness have not yet been tested.

	Outcome measure	Develop-ment	Content validity	Structural validity	Internal consistency	Test-retest reliability	Intra-rater reliability	Inter-rater reliability	Measurement error	Criterion validity	Hypotheses testing for construct validity	Hypotheses testing for known-group validity	Responsiveness
Category 1	BESTest				0		0	+			++	++	++
	Mini-BESTest				++		++	++		++	++	++	++
	Short-BESTest				++		-	-		++	++		0
	Brief-BESTest				0		-	++	-	++	++	++	0
	CB&M scale			+							++		++
	Four-Square Step Test						-	+			++	++	
Category 2 (A)	L-Shape Walk Test						0	+			++		
	Turning in L-shape Walk Test						0				++	++	
	Parallel Walk Test					+	0	+			++		
	Sideways Walk Test					+	-	+	+		++		
	Standardised Walking Obstacle Course Test					+	0	+	+		++		
	Long-distance Corridor Walk Test					+		+	+		++		
	The Timed 180^{O} Turn Test					+	0	+	+		++		
	The Cone Evasion Test						-	0			++		
	Figure of 8 walk test					+	0	+			++		
	Six-Spot Step Test					+	+	+	+		++	++	
	3m Backward Walk Test					0	0	0	0		++		
	TUG Test					+	-		0		++	-	+
	TUG ^{motor} Test					+	0		+		++		
	Expanded TUG Test						0	0					
	TUG – ABS	+	0				-	0		++	++	++	

	TUG – Obstacle Cross Test					+		+			++		
	Timed 360° Turn Test					+	+	+			++	++	
	Loaded and Unloaded Timed Stair Test						+				++	++	
Category 2 (B)	The Shuttle Walk Test					+			+		++		
	EFAP							+			++		
	mEFAP					+		+	+		++		+
	DGI					+		+	+		++	++	++
	mDGI					0			0			++	
	FGA					+	+	+			++		++
Category 3	Cognitive and motor tasks with walking tests					+			+		+	++	
	Cognitive and auditor tasks with walking tests					0			0		++		
	Walking and turn with auditory test					+							

Table 3-4 The quality of the methodological design per OM psychometric properties. Balance Evaluation System Test (BESTest). Community balance and mobility scale (CB&M) scale. Dynamic Gait Index (DGI). Emory Functional Ambulation Profile (EFAP). Functional Gait Assessment (FGA). modified DGI (mDGI). modified EFAP (mEFAP). Timed Up and Go Test (TUG test). TUG Assessment of Biomechanical Strategies (TUG-ABS). COSMIN grading system: very good (++), adequate (+), doubtful (0), inadequate (-).

3.3.5 *Quality of statistical method*

Table 3-5 presents the overall summary of the quality of the statistical method from the methodological design with the highest quality according to COSMIN criteria for each OM property.

3.3.5.1 Category 1: dynamic balance OM

The intra-rater and inter-rater reliability statistical methods quality for the Mini-BESTest (294) were very good, however, for BESTest (432), BESTest short versions (427,433), and Four-Square Step Test (434) it was found to be adequate. The quality of statistical methods used for internal consistency for BESTest (415) and the Brief-BESTest (433) were adequate and for the Mini-BESTest and Short-BESTest (425) were very good.

In all dynamic balance OM, the construct (294,415,427,434,457) and the known-group (293,294,415,424,431,467) validities have very good statistical methods quality except for the criterion validity for the Short BESTest (427), as shown in Table 3-5. For responsiveness, the quality of statistical methods used for the BESTest, BESTest short versions (416,427), and the Community Balance and Mobility scale (457) were rated as very good, Table 3-5.

3.3.5.2 Category 2: functional walking OM

The quality of statistical methods was very good for all reliability ~~types~~ for all OM (291,297,437,438,440,444–447,450,453,454,418,455,456,461,464,419,421–423,429,435,436) and adequate for test-retest reliability of the TUG test (428), and modified-DGI (464), and for the inter-rater reliability for Emory Functional Ambulation (423,461).

The quality of statistical methods used for construct and known-group validities for all functional walking OM was rated as very good (417,418,439,440,446,447,450,453–456,461,422,423,428,429,435–438). However, according to COSMIN criteria the statistical methods was rated as doubtful and inadequate for known-group validity for the TUG (428), and modified DGI (464), respectively. The results are presented in Table 3-5. For responsiveness, the quality of statistical methods used was rated as very good for the TUG test, DGI, and FGA (297,459) and adequate for Emory Functional Ambulation (423), the results are presented in Table 3-5.

3.3.5.3 Category 3: DT while walking OM

Test-retest reliability had a very good quality of statistical methods in two studies (430,448), and adequate in one study (467). For construct and known-group validities, the quality of statistical methods was very good for all studies (430,449), The results are presented in Table 3-5.

	Outcome measure	Development	Content validity	Structural validity	Internal consistency	Test-retest reliability	Intra-rater reliability	Inter-rater reliability	Measurement error	Criterion validity	Construct validity	Known-group validity	Responsiveness
Category 1	BESTest				++		+	+			++	++	++
	Mini-BESTest				++		++	++		-	++	++	++
	Short-BESTest				++		+	+		-	++		++
	Brief-BESTest				++		+	+	++	-	++	++	++
	CB&M scale			++							++		++
	Four-Square Step Test						++	+			++	++	
Category 2 (A)	L- Shape Walk Test						++	++			++		
	Turning in L-shape Walk Test						++					++	
	Parallel Walk Test					++	++	++			++		
	Sideways Walk Test					++	++	++	++		++		
	Standardised Walking Obstacle Course Test					++	++	++	++		++		
	Long-distance Corridor Walk Test					++		++	++		++		
	The timed 180^{O} Turn Test					++	++	++	++		++		
	The Cone Evasion Test						++	++			++		
	Figure of 8 Walk Test					++	++	++			++		
	Six-Spot Step Test					++	++	++	++		++		
	3m Backward Walk Test					++	++	++	++		++		
	TUG Test					+	++		++		++	-	++
	TUG ^{motor} Test					++	++	++	++		++		

	Expanded TUG Test						++	++					
	TUG – ABS	++	++				++	++		++	++	++	
	TUG – Obstacle Cross Test					++		++			++		
	Timed 360° Turn Test					++	++	++			++	++	
	Loaded and Unloaded Timed Stair Test						++				++	++	
Category 2 (B)	The shuttle walk test					++			++		++		
	EFAP							+			++		
	mEFAP					++		+	+		++		+
	DGI					++		++	+		++		++
	mDGI					+			++			0	
	FGA					++	++	++			++		++
Category 3	Cognitive and motor tasks with walking tests					+			++		++	++	
	Cognitive and auditor tasks with walking tests					++			++		++		
	Walking and turn with auditory test					++							

Table 3-5 The quality of the statistical method (SM) for each psychometric property. Balance Evaluation System Test (BESTest). Community balance and mobility scale (CB&M scale). Dynamic Gait Index (DGI). Emory Functional Ambulation Profile (EFAP). Functional Gait Assessment (FGA). modified DGI (mDGI). modified EFAP (mEFAP). Timed Up and Go Test (TUG test). Timed Up and Go Test - Assessment of Biomechanical Strategies (TUG-ABS). COSMIN grading system: very good (++), adequate (+), doubtful (0), inadequate (-).

3.3.6 Psychometric properties

Inter-rater reliability and hypothesis testing for construct validity were the most evaluated properties across all OM categories. The following sections summarise the psychometric properties for each OM investigated in the studies in this review, according to the best methodological design among the included studies.

3.3.6.1 Category 1: dynamic balance OM

The BESTest had the best overall psychometric properties, showing very good quality according to the COSMIN criteria for good measurement properties, intra-rater reliability (ICC= 0.98) (432), inter-rater reliability (ICC= 0.93) (432), and internal consistency (Cronbach's α= 0.96)(293). In addition, the identified construct validity for the BESTest showed a strong correlation with other OM such as the Postural Assessment Scale (Spearman correlation= 0.96) (415), and moderate correlation with postural stability and limits of stability as tested by Biodex Balance System (Pearson's correlations -0.62, 0.60 respectively).

Known-group validity and cut-off score to differentiate between fallers and non-fallers was identified (69.44% of the total score) (293), and it also demonstrates high responsiveness, as calculated by the Area Under the Curve (AUC= 0.92) with no floor or ceiling effect (416). Similar psychometric properties were reported for the BESTest short versions, yet the Mini-BESTest demonstrated the best responsiveness (AUC=0.89), and the lowest ceiling effect compared to the Short- and Brief-BESTest (416,420,424–427). The cut-off score for Mini-BESTest to differentiate stroke survivors with or without a history of falls was also identified and was 17.5 out of 28 (the total score) (294).

Other OM in the dynamic balance category include the Community Balance and Mobility scale and the FSST, and construct validity was identified for both of these (434,457). However, structural validity was determined only for CB&M (457). The Four-Square Step Test had excellent inter-rater reliability (ICC=0.99) and good intra-rater reliability (ICC=0.83) (434). Reliability was not tested for the Community Balance and Mobility scale; however, responsiveness was identified (457,458). The results are presented in Table 3-6.

Outcome measure	Reliability					Validity					Responsiveness
	Internal consistency	Test-retest	Intra-rater	Inter-rater	Measurement error	Content	Criterion	Structural	Construct (Correlation with)	Known group (Cut-off score)	
BESTest	Cronbach's α= 0.96		ICC= 0.98	ICC= 0.93					PASS rho = 0.96	69.44%	AUC= 0.92 No floor effect, ceiling effect in 4%
Mini-BESTest	6 strata identified		ICC= 0.97	ICC= 0.96					BBS rho= 0.96	17.5 (5.5 points)	AUC= 0.89 No floor effect, ceiling effect in 7%
Short-BESTest	5 strata identified		ICC= 0.98	ICC= 0.95							No floor effect, ceiling effect in 11%
Brief-BESTest	Cronbach's α = 0.82		ICC= 0.97	ICC= 0.97	SEM= 0.77				BBS rho= 0.93	<14 (1.17 point)	AUC= 0.77 No floor effect, ceiling effect in 15.7%
CB&M scale								14-item unidimensional CB&M scale	BBS rho= -0.83		SRM= 0.83
FSST			ICC= 0.83	ICC = 0.99					backward reaction *r* =0.64		

Table 3-6 A summary of findings for the statistical outcomes for the psychometric properties of each OM in the dynamic balance category. Alpha correlation (α). Area Under the Curve (AUC). Berg Balance Scale (BBS). Balance Evaluation System Test (BESTest). Community Balance and Mobility (CB&M) scale. Fugl-Meyer Assessment (FMA). Fugl-Mayer Assessment- Lower Extremity (FMA-LE). Four Square Step Test (FSST). Intraclass Correlation Coefficient (ICC). Postural Assessment Scale for Stroke (PASS). Pearson's Correlation (r). Spearman's Correlation (rho). Standard Error of Measurement (SEM). Standard Response Means (SRM).

3.3.6.2 Category 2: functional walking OM

All OM in the functional walking (group A) have excellent reliability (their Intra Class Correlation Coefficient (ICC) ranged from 0.82 to 1). For construct validity, the Six-Spot-Step Test Walk test had the highest positive correlation with the TUG test (r = 0.92), the higher scores in the Six-Spot-Step Test (i.e., time duration) were correlated with the higher scores in the TUG test (429). The TUG test had a high negative correlation with the 6-Minute Walking Test (rho= -0.96), (i.e., a lower time in the TUG test correlated with more distance in the 6-Minute Walking Test) (428). Responsiveness was identified for the TUG test only, and moderate responsiveness for pre- and post-treatment was identified (443). However, responsiveness to change between subgroups with different ages or with varying time post-stroke was low (459). The results are presented in Table 3-7.

Also, all functional walking OM (group B), showed excellent reliability (ICC ranging from 0.92 to 1). For construct validity, the highest positive correlation was found between the FGA and the BBS, and similarly with the 6-Minute Walking Test (i.e., the higher scores in the FGA were correlated with higher scores in the BBS and with the 6-Minute Walking Test) (417). Known-group validity and cut-off score to identify fallers and non-fallers were determined for the DGI only (442,464). Both the DGI and FGA had no floor effects after 5 months of rehabilitation, however, a lower ceiling effect was identified for FGA (5.7%) compared to DGI (11.7%) (297). The results are presented in Table 3-8.

Outcome measure	Reliability					Validity					Responsiveness
	Internal consistency	Test-retest	Intra-rater	Inter-rater	Measurement error	Content	Criterion	Structural	Construct (Correlation with)	Known- group (Cut-off score)	
Parallel walk test		ICC= 0.97	ICC=0.96	ICC= 1					TUG test rho= 0.84		
Sideways walk test		ICC= 0.99	ICC=0.96	ICC= 0.99	SEM=1.85 sec				FMA-LE rho= -0.74		
Standardised walking obstacle course test		ICC= 0.96	ICC= 0.97	ICC= 0.99	SEM=3.9 sec SEM=4 steps				TUG test rho= 0.76		
Long-Distance Corridor Walk Test		ICC= 0.97		ICC= 0.99					TUG test rho= 0.83		
The timed 180° turn test		ICC= 0.97	ICC=0.97	ICC=0.97					TUG test rho= 0.71		
The cone evasion test			ICC=0.98	ICC=0.97					TUG test rho= 0.45		
Figure of 8 walk test		ICC= 0.97	ICC=0.96	ICC=0.99					TUG test rho= 0.89[64]		
Six-Spot Step Test		ICC= 0.96	ICC = 0.96	ICC= 0.99	SEM= 3.42				DGI rho= -0.83 FSST r= 0.86 TUG test r= 0.92 Sit to Stand r= 0.57 ABC rho= -0.59 BBS rho= -0.53 FMA rho= -0.52		
3-metre backward walk test		ICC = 0.98	ICC = 0.96	ICC= 0.99	SEM= 1.11sec				BBS r= 0.69 TUG test r= 0.85 Time from GAITRite		

									ICC= 0.96 ICC= 0.97		
TUG test		ICC = 0.95	ICC= 0.96		SEM=1.16				6-min walk test rho= -0.96	22.6 ± 8.6	
TUG motor test		ICC = 0.97	ICC = 0.97	ICC = 0.99					FMA r= -0.69		
Expanded TUG test		ICC= 1	ICC= 0.99								
TUG – ABS		*K*= 0.89-1	*K*= 0.80				*K* =0.72-1	*K* =0.09-1	TUG time r= -0.80	97.9%	
TUG obstacle cross test			ICC= 0.96						TUG test rho= 0.91		
Timed 360° turn test		ICC=0.94	ICC=0.95	ICC=0.99					BBS r= -0.76 10-m walk test r=-0.66 TUG test r=0.76	3.43 to 3.49 seconds	
Loaded and unloaded timed stair test		ICC= 0.96		ICC=1					TUG test r=0.87	Unloaded test 23 seconds Loaded test 26 seconds	

Table 3-7 A summary of findings for the statistical outcomes (SO) for the psychometric properties of each OM in the functional walking outcome measures (group A) category. Alpha correlation (α). Area Under the Curve (AUC). Berg Balance Scale (BBS). Fugl-Meyer assessment (FMA). Fugl-Mayer Assessment- Lower Extremity (FMA-LE). Four Square Step Test (FSST). Intraclass Correlation Coefficient (ICC). Kappa agreement (K). Postural Assessment Scale for Stroke (PASS). Pearson's Correlation (r). Spearman's Correlation (rho). Timed Up and Go Test (TUG test). Assessment of Biomechanical Strategies (TUG-ABS). 10-metre walk test (10mWT).

Outcome measure	Reliability					Validity					Responsiveness
	Internal consistency	Test-retest	Intra-rater	Inter-rater	Measurement error	Content	Criterion	Structural	Construct (Correlation with)	Known group (Cut-off score)	
The shuttle walk test		ICC = 0.96			SEM= 11				6-minute walk test *r*= 0.65		
EFAP				ICC= 0.99					10mWT rho= -0.71		
mEFAP		ICC= 0.99		ICC= 0.99					10mWT rho= 0.88		SRM=1
DGI		ICC= 0.96		ICC= 0.96	SEM= 0.97				BBS rho= 0.83	DGI-8 ≤16.5 DGI-4 ≤9.5	No floor effect, ceiling effect 11.7%
mDGI		α = 0.97								Correlation between stroke vs controls and VD *r*= 0.96	
FGA		ICC= 0.92	ICC= 0.99	ICC= 0.93					BBS rho= 0.93		No floor effect, ceiling effect 5.7%

Table 3-8 A summary of findings for the statistical outcomes (SO) for the psychometric properties of each OM in the functional walking outcome measures (group B) category. Alpha correlation (α). Berg Balance Scale (BBS). Dynamic Gait Index (DGI). Emory Functional Ambulation Profile (EFAP). Functional Gait Assessment (FGA). Intraclass Correlation Coefficient (ICC). modified DGI (mDGI). modified EFAP (mEFAP). Pearson's Correlation (r). Spearman's Correlation (rho). Standard Error of Measurement (SEM). Standard Response Means (SRM). Vestibular Disorder (VD). 10-metre walk test (10mWT).

3.3.6.3 Category 3: DT while walking OM

This category consists of various tests for walking and secondary tasks. The walking tests consist of comfort and maximum speed, backward walking, walking across an obstacle, and a walk and turn test (430,448,449). Secondary tasks include cognitive tasks such as attention-demanding tasks namely verbal fluency and serial subtractions (449), and short memory tests, for example shopping test recall (430), or Auditory Stroop test (AST) (448). There was some inconsistency in the testing procedure among studies, for example in Yang et al (449), the single cognitive tests were performed after the DT test and the participants were allowed to respond for the cognitive tests alone according to their previous time recorded in the DT tests. In Tsang et al (430) cognitive tasks were classified into low and high categories, for example for verbal fluency test, low category test was naming in random, but for the high category test it was naming in a more confined selection.

All tests in single motor-related tasks demonstrated good to excellent test-retest reliability, (ICC ranged from 0.80 to 0.97) (430,449), and moderate to good reliability for single cognitive-related tasks (ICC ranged from 0.63 to 0.87) (430,449). Similarly, under DT conditions, the reliability of motor-related tasks was higher than cognitive-related tasks, (ICC ranged from 0.70 to 0.98; and from 0.50 to 0.89 respectively) (430,449).

The highest reliability under DT conditions for the motor tasks was walking across an obstacle while simultaneously practising the AST (ICC=0.98) (430). However, for cognitive tasks, the highest reliability was for serial subtractions while walking on level-ground (ICC=0.89) (430). On the other hand, the lowest reliability under DT conditions for the motor tasks was for walking across an obstacle while simultaneously practising serial subtractions (ICC= 0.70) (68); and for the secondary tasks it was for AST reaction time while simultaneously walking across an obstacle (ICC=0.50) (430).

For construct validity, hypotheses were tested for motor walking tests, and cognitive tasks (449). Firstly, the motor tests were correlated with the TUG test under DT conditions and the highest correlation was between walking at a self-selected speed while simultaneously practising a verbal fluency task and TUG test, as well as walking at a self-selected speed while doing serial subtraction and TUG test (r= 0.93 for both) (449).

Secondly, the cognitive tasks were correlated with similar cognitive tasks while performing the TUG tests (i.e., the verbal fluency task while walking across obstacle were correlated to the verbal fluency task while performing the TUG test) (449). The cognitive tasks were also correlated with MOCA scores (448). The highest correlation was identified to be between the serial subtraction while walking at a self-selected speed and the serial subtraction while walking in the TUG test (r=0.65) (449), results are presented in Table 3-9.

Outcome measure	Reliability					Validity					Responsiveness
	Internal consistency	**Test-retest**	**Intra-rater**	**Inter-rater**	**Measurement error**	**Content**	**Criterion**	**Structural**	**Construct (Correlation with)**	**Known group (Cut-off score)**	
Cognitive and motor tasks with walking tests		Single task: Walking time ICC= 0.93 Cognitive related ICC=0.73 DT-Motor ICC= 0.93 DT-Cognitive ICC= 0.87			SEM=6.90				TUG test Walking time r= 0.93 Cognitive r=0.65	AUC= 0.51-0.63	
Cognitive and auditory tasks with walking tests		Single task: Motor ICC= 0.98 Cognitive ICC= 0.89 DT-Motor ICC=0.98 DT-Cognitive ICC=0.89			SEM=1.70 SEM=2.80				MoCA r= 0.56		
Walking and turn with AST		Single task: Motor ICC= 0.97 AST ICC = 0.67 DT ICC= 0.97									

Table 3-9 A summary of findings for the statistical outcomes (SO) for the psychometric properties of each OM in the dual task walking outcome measures. Auditory Stroop Test (AST). Dual task (DT). Intraclass Correlation Coefficient (ICC). Montreal Cognitive Assessment (MoCA). Pearson's Correlation (r). Standard Error of Measurement (SEM). Timed Up and Go Test (TUG Test).

3.4 Discussion

A broad range of dynamic balance, functional, and DT walking OM were identified. The OM were classified into a first category assessing dynamic balance and included tasks assessing dynamic balance control mechanisms, and a second category assessing functional walking, which was further separated into two groups, to assess single and complex walking tasks. The OM for DT walking can be used to assess motor-cognitive interference, in addition to assessing a stroke survivor's capacity for DT while walking. The dynamic balance OM such as the BESTest aimed to test reactive postural control, and sensory orientation such as standing on foam, and walking and turning one's head. Furthermore, the functional walking OM covered more complicated tasks such as walking with one's eyes closed.

The BESTest (293,415,416,426,432) and Mini-BESTest (420,424,425,427,431) from category one (dynamic balance) and the TUG (291,428,443–446,459,462), DGI (440–442,464) and FGA (297,417,421) from category two (functional walking), were the most studied OM for stroke survivors. The findings in this review are consistent with findings from a recent study from a focus group by the third Stroke Recovery and Rehabilitation Roundtable. This involved 13 worldwide experts in the field of mobility rehabilitation and recommended the following OM: the BBS and the Mini-BESTest for balance, the 10-metre Walk Test for walking speed, the 6-Minute Walk Test for walking endurance, and the DGI for complex walking (387,388), however, the FGA and DT while walking were not cited.

The current review showed that the most investigated psychometric properties tested were reliability and validity. All identified OM for dynamic balance and functional gait were tested for reliability and construct validity, however, responsiveness was not determined for all OM in categories one and two. The quality of methodological design and statistical methods for testing reliability, validity, and responsiveness in the included studies ranged from very good to inadequate according to the COSMIN tool for good measurement (10,405,411). Reasons for low rating of methodological design and statistical methods for reliability, validity, and responsiveness will be discussed in the following section.

In category three, DT while walking OM included walking with a simultaneous secondary auditory Stroop test, or motor, or cognitive task. Although dynamic balance and functional walking OM help in setting treatment goals to improve motor functional activity, DT walking OM can help in providing more individualised goals, depending on motor-cognitive interference. Reliability and construct validity were determined for DT walking OM (430,448,467), but responsiveness was not tested. The quality of methodological design and statistical methods for reliability and validity of DT gait OM will be discussed under the reliability and validity of DT gait while walking OM, in "section 3.4.4 Reliability and validity of DT while walking OM".

3.4.1 Reliability of dynamic balance and functional walking OM

Although the quality of the methodological design of testing for all types of reliability ranged from very good to adequate according to COSMIN criteria, methodological design was rated as inadequate for intra-rater reliability in 8 studies (291,415,422,427,433,434,437,446), and for inter-rater reliability in 3 studies (415,427,446). The quality of the methodological design was inadequate because the duration between the measurement tests was noticeably short and insufficient to prevent recall. The time recommended by the COSMIN criteria is 14 days, and it is considered that status will not change between tests for those with chronic conditions (405). In addition, when evaluating reliability, assessors should score the patient independently, but there were unclear or insufficient details in some studies on whether the rater (assessor) assigned the score without knowledge of a score by the other assessor for the same patient; and thus the quality of methodological design was doubtful or inadequate for some studies according to COSMIN criteria (409). Reliability testing can be improved by introducing standardised protocols for investigating each type of reliability (400). Furthermore, scoring can be affected using a walking aid as well as by the level of physical assistance or encouragement provided by the assessor while performing the assessment. However, this information is not normally included, which can further affect reliability (468).

The quality of statistical methods was rated as very good for most studies included, however, a variation in the type of the Inter Classification Coefficient (ICC) used was noted. The ICC is recommended by the COSMIN tool (409) for continuous measures. However, the results of testing the reliability are sensitive to the type of ICC model used, and might result in overestimation of reliability if the type of ICC was not used accurately (9,412,469).

The two-way mixed effect $ICC_{(3)}$ was used for the test-retest reliability in two studies (439,447) which resulted in a high ICC value, and according to COSMIN criteria the statistical methods was rated as less appropriate. The $ICC_{(3)}$ always results in larger values than the one-way random effects model $ICC_{(1)}$ and the two-way random effect model $ICC_{(2)}$ (413). $ICC_{(3)}$ is used to test consistency, does not consider systematic error, and is always higher than the other form of ICC, which is used to test the agreement ($ICC_{(1)}$ or $ICC_{(2)}$) (7,470). Therefore, $ICC_{(3)}$ is considered less appropriate than $ICC_{(1)}$ or $ICC_{(2)}$ for reliability in rehabilitation measures (10). A recent study suggests calculating both the ICC for consistency $ICC_{(3)}$ and agreement $ICC_{(1)}$ or

$ICC_{(2)}$ to provide further complementary information (471). Except for the type of ICC used in the included studies, no other flaws were identified for the statistical methods used for reliability.

3.4.2 Validity of dynamic balance and functional walking OM

The concept of validity includes 5 subtypes according to the COSMIN guidelines (10,409), which have been discussed under section "3.2.3.1 Psychometric properties terminology". Among studies included in the current review, construct validity was the more frequent type of validities which was determined for the OM in the included studies. Despite the importance of content and structural validity as fundamental types of validity (407), they were not identified for dynamic balance and functional gait OM for stroke survivors, except for the Community Balance and Mobility scale (457) and the TUG test (445).

A lack of content validity indicates missing a particular assessment essential for stroke survivors' rehabilitation, such as precise assessment of turning while walking. Although the turning function is included in the BESTest, BESTest short forms, FGA, Six-Spot-Step test, and Cone Evasion test, the turn function in all these OM is rated from the time of task completion, and number of steps to complete, in addition to level of unsteadiness in the FGA. Furthermore, in the Six-Spot-Step Test and Cone Evasion test, the scoring of turn function also includes the number of the blocks moved when turning (i.e., blocks are used in the Six-Spot-Step and Cone Evasion Tests).

Meanwhile, recent studies indicate that turning in stroke survivors not only requires significantly more time and number of steps compared to healthy controls (472), but the mechanism of turning also involves a greater contribution from the upper body and a greater degree of lateral trunk bending, which indicates gluteus medias muscle weakness and poor control (473,474). Therefore, it can be suggested that lateral trunk bending while turning is recorded, and included as part of the scoring, in addition to the time required to complete the turn and number of steps. Furthermore, although turning towards the paretic or non-paretic side might require the same time and number of steps (474), stroke survivors who experience falls access narrow spaces from the paretic side (475). It can be suggested that, in addition to the number of steps and time required to complete the turn, the mechanism of turning, such as the direction of turn concerning the hemiparesis side, can be noted in scoring the turning function for stroke survivors.

Construct validity reflects the degree to which the scores of a measurement instrument are consistent with hypotheses about the relationship with scores of other instruments (7,410). Construct validity was the most common type of validity tested for the included OM. Although construct validity is less powerful than the criterion validity, it can provide evidence of validity (7). The OM used for correlation to identify the construct validity in the included studies were mostly for static balance or motor impairment (i.e., lower functional level).

The correlation between dynamic balance or functional gait and OM at a lower level of motor function was strong, but this correlation is inadequate since the OM are fundamentally assessing different variables (476). For example, the Fugl-Meyer Assessment or BBS was used to assess construct validity for dynamic balance and functional gait, however, the aim of the FMA is to assess motor impairment in the initial stages of recovery or for patients with severe disability (477), while the BBS assesses static balance (290).

Both the Fugl-Meyer Assessment and BBS do not include tasks to test dynamic balance, and functional walking. Therefore, hypothesis testing for construct validity using an OM to assess motor recovery at a lower level of motor functioning can result in statistically significant correlation but fail to test the strength of the association which is required for hypothesis testing for construct validity for OM to assess walking in a functional level (7).

The TUG test was also used to test construct validity, but it assesses gait speed only. There is a need to use a test with a similar functional level to provide robust construct validity, for example, the DGI was used to determine the construct validity for the Six-Spot-Step Test (451). The DGI assesses balance while walking in response to external demands (4) and was appropriate for testing the construct validity for the Six-Spot-Step Test.

Known-group validity reflects the difference between the subgroups, and it is important to identify the cut-off scores and subsequently help in setting the treatment goals which can be tailored according to patients needs for example if patients are at risk of falls (478). Interestingly, in the included studies the known group validity to identify stroke survivors and healthy controls and to differentiate between fallers and non-fallers among stroke survivors was determined for the BESTest, Mini-BESTest, Brief-BESTest, Six-Spot-Step Test, TUG test, DGI, and the modified DGI.

3.4.3 Responsiveness of dynamic balance and functional walking OM

Responsiveness is a primary psychometric property which indicates the capacity of an OM to detect a meaningful change in patient response pre-post treatment or between subgroups (7,406,411). The BESTest and Mini-BESTest demonstrated the highest responsiveness compared to short forms of BESTest and Community Balance and Mobility scale. Moreover, in category 2 the DGI and FGA had better responsiveness than the TUG test. Therefore, the BESTest, Mini-BESTest, DGI, and FGA can be recommended to identify pre-post treatment change.

The methodological quality for assessing the responsiveness of an OM can be affected by the approach to testing the responsiveness. In the construct approach to testing the responsiveness of an OM for pre-post treatment, the treatment should be clearly described to recognise if there are floor and ceiling effects recorded for the measurement in relation to the type of treatment provided (10). However, among the included studies which investigated the responsiveness, the treatment was not clearly described, which indicates the need for further studies and clear description of the treatment interventions in studies aimed to test the responsiveness of OMs.

3.4.4 Reliability and validity of DT while walking OM

The limitation in OM designed to test DT walking is noticeable in stroke rehabilitation (479), as well as in other conditions, such as in vestibular disorders (480). There is no consensus on what type of activity the DT should be, i.e. motor (simple or complex), auditory, or cognitive. Additionally, test procedures, task difficulty, and scoring differ heavily between studies, which might affect the generalisability of these measures (481). For example, cognitive tasks were varied, and included visual and auditory Stroop tasks (discrimination and decision making), serial subtractions (mental tracking), spelling, word list generation, or reciting alternate letters of the alphabet (verbal fluency task) (480). A systematic review by Danneels et al (2018) identified that reaction time, working memory, and visuospatial abilities were not covered within cognitive DTs tests in the included studies (480). A variety of cognitive DT will need to be assessed for a more comprehensive indication of the impacts on DT gait assessment, in addition, the level of difficulty of tasks differs, as does the impact on scoring and comparability (481).

In a recent study by Pavlou et al (2023) for people with vestibular disorder, it was found that the type of DT - motor or cognitive (numerical and literacy) tasks - can affect gait performance (481). The DT cost, which is calculated to assess DT interference, showed that a numerical task in the form of subtracting 7 while performing the FGA test demonstrated the highest effect on the DT cost (481). However, a low-demand numeracy task such as subtracting from 1 while performing the FGA test showed results similar with no additional task while performing the FGA test, since the low-demand numeracy task is more rhythmic and can cue step patterns (481,482).

In the DT studies included in the current review, walking while carrying a cup was the simultaneous motor task used to assess DT. However, carrying a cup while performing the FGA test had a minimal effect on DT cost, since walking while carrying a cup can be identified as a single motor complex task (481,483). Both gait and carrying a cup require postural control, and the inertial forces created by the gait cycle while walking are used for carrying the cup (481,483). Therefore, the cup represents an added postural constraint which increases task complexity but not the number of tasks performed, and is insufficient to show a DT interference effect (481,483). A motor DT needs to be separable in each task goal and should be distinctly measured, therefore, it is suggested to have walking while texting on a mobile phone as a motor DT gait assessment (481,483).

External cognitive tasks have been shown to affect functional gait (484). The effect of DT gait performance depends on the cognitive task type and gait task complexity, but it is important to note that performance is also associated with a person's ability to allocate cognitive resources and the performer's expertise, which could be documented in scoring the DT gait OM (481).

The reliability for cognitive-related tasks was found to be lower than the reliability for motor-related tasks in the included studies for the DT while walking OM. This agrees with findings from previous studies for older adults (485,486). Moreover, the reliability of cognitive tasks in the included studies varied; the highest reliability was in serial subtractions while walking at a self-selected speed (430). However, the lowest reliability was for reaction time from the auditory Stroop test while walking and crossing the obstacle, which was obtained in the same study (the same sample) (430). The low reliability of the auditory Stroop test in DT condition was consistent with a previous study in people with vestibular disorder (480). The difference in reliability between the auditory Stroop test and serial subtraction DT tasks may be due to the high accuracy reported for the AST, with most participants achieving 100% accuracy (480). Serial subtraction has been identified as the DT condition that has the highest cognitive cost (487). Higher accuracy leads to low variability between participants, and therefore a low ICC value, while the opposite is shown for serial subtractions (480,488).

Another factor that might affect the reliability of the secondary cognitive task is the complexity of the primary motor task. The highest reliability for the secondary cognitive task was from walking at a self-selected speed, which was identified as the simplest motor task (421). Walking while obstacle-crossing was found to be the most difficult task for stroke survivors (421). Thus, the reliability of the secondary cognitive task was low compared to the reliability of other secondary cognitive tasks while performing other motor tasks. Further studies are required to understand whether the reliability of a secondary cognitive task can be affected by the difficulty of the primary motor-related task.

Data on responsiveness was lacking for DT gait OM in the included studies. Training with DT has been shown to provide greater improvements in balance, gait, and quality of life and reduces the risk of falls compared to traditional exercises for stroke survivors (403). To assess pre-post-treatment improvement, the responsiveness of DT gait OM must be investigated, as undetermined responsiveness may result in a misrepresentation of an intervention's true benefit (7).

3.4.5 Limitations of the review

The present review includes many studies, and the identified OM were appraised by the COSMIN tool to assess the risk of the bias. The terminology of psychometric properties and the quality assessment were based on the COSMIN guideline, which provides a robust and thorough assessment for OM.

However, the present review is limited by the inclusion of studies published in English only. In addition, the registration of the review in the international prospective registration of systematic reviews (PROSPERO) was not accepted because the data extractions were initiated before the registration.

Furthermore, the study population was not homogeneous, which limits the generalisability of findings. In addition, the current review focused on primary psychometric properties (reliability, validity, and responsiveness).

Although the Mini-BESTest has shown an association with community ambulation (i.e., higher scores on the Mini-BESTest were related to higher levels of community ambulation) in a cohort study (83), the interpretability (i.e., the qualitative meaning to a patient) and the transferability of OM to real-world function, were not studied in this review because of limited time and absence of a specific tool to assess the risk of bias. Both characteristics are desirable objectives and need further evaluation for OM since stroke survivors may achieve high scores in the laboratory-based assessment but in real-world situations cannot perform the same level of functioning. For example, stroke survivors report that crossing the road is difficult, despite motor functional level and gait speed improvements noted in a study by Robinson et al (2013) (250).

3.4.6 Conclusion

In conclusion, the OM were separated into three categories according to stroke survivors' level of function, dynamic balance, functional walking, and DT while walking. The OM which demonstrated the best psychometric properties were BESTest and Mini-BESTest for dynamic balance and DGI, FGA, and TUG test for functional gait OM. For more complex motor functional capacity, and to assess higher motor function, which is close to normal simulation of activity in the community, DT while walking OM should be used since such tests will measure the challenge in motor tasks in addition to cognitive-motor interference on performance (487).

According to the aim of the OM and the rehabilitation goals, the information in this review may help clinicians and researchers in choosing the most suitable OM, and which demonstrates good psychometric properties. Further studies with high quality methodological design are needed to test undetermined psychometrics, in addition to developing OM which are more aligned with stroke survivors' specific, and commonly reported functional limitations.

Chapter 4: General Methodology

4.1 Brief Introduction

There are various methods used to assess health, based around different concepts. Wilson and Cleary (1995) presented a conceptual model for measuring the concept of health-related quality of life, which is a way of distinguishing various levels of clinical and health measurement (489), as shown in Figure 4-1. The model started from biological and physiological variables, which result in symptom status and affects functional status, general health perceptions and overall quality of life. All these are linked to individual and environmental characteristics. Therefore, measurement levels range from the molecular and cellular level to the impact of health or disease on individuals. Furthermore, measurements should include personal factors such as psychological and social aspects in addition to the characteristics of the environment (7).

Similar to the Wilson and Cleary conceptual model for health measurement (489), the International Classification of Functioning, Disability and Health (ICF) framework was developed by the World Health Organisation (WHO) to classify health conditions and diseases to body impairment, activity limitations and participation (490). Other contextual factors included in the ICF model are personal circumstances such as educational level. This is because environmental conditions also have an influence on health outcomes (490). The ICF map is presented in Figure 4-2.

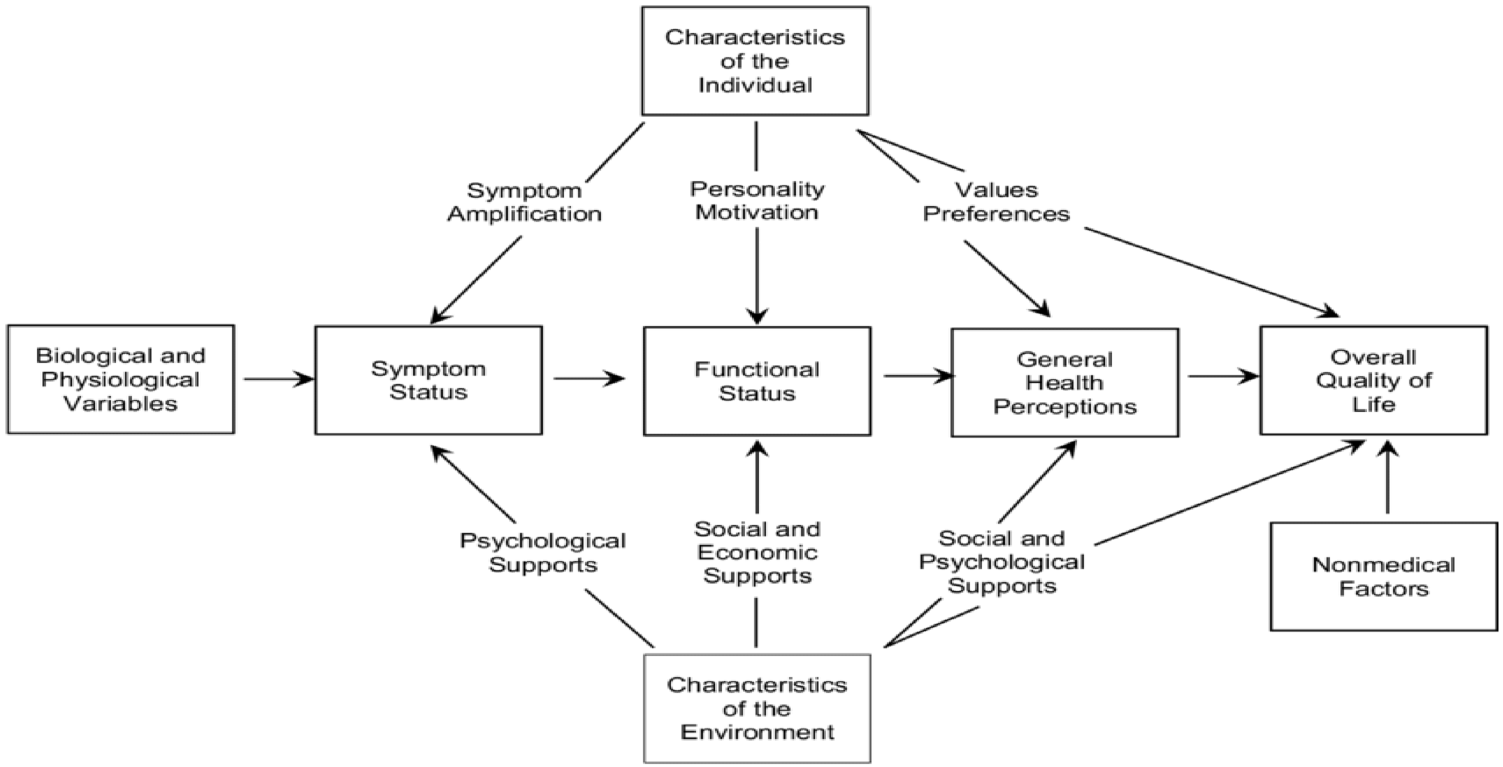


Figure 4—1 Wilson and Cleary's conceptual model for measuring the concept of health-related quality of life (489).

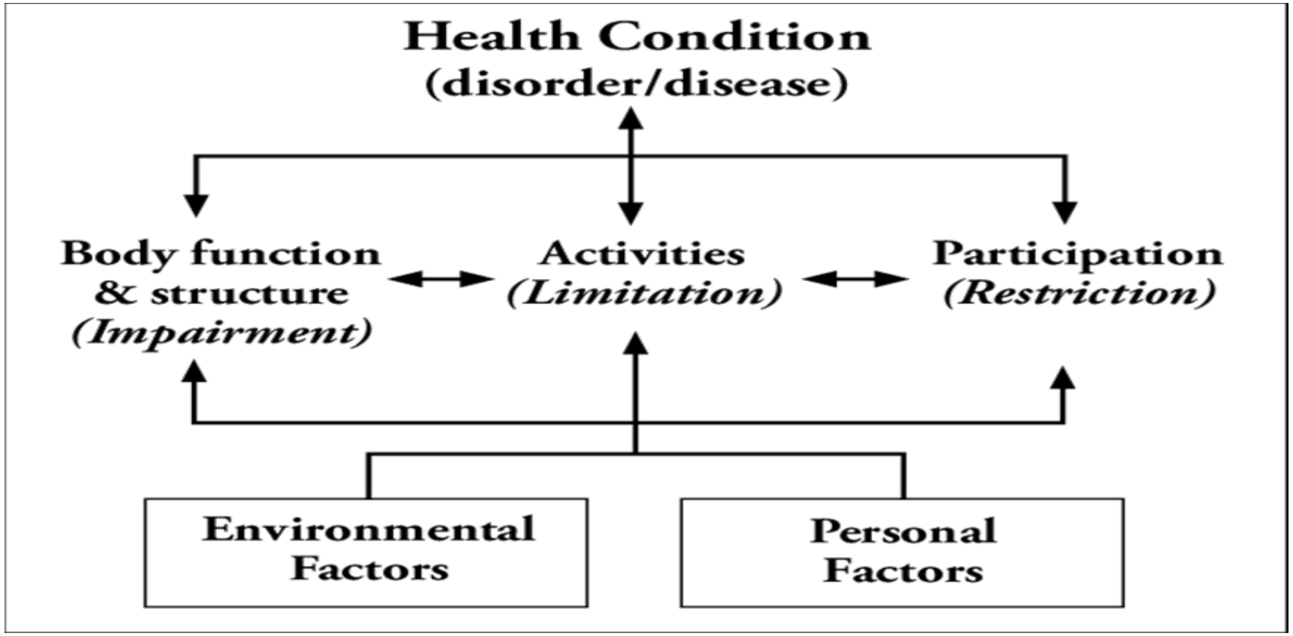


Figure 4—2 The International Classification of Functioning, Disability and Health (ICF) map (490).

For diagnosis purposes, the focus of measurement is on finding morphological changes in tissues, disturbances in physiological process, or pathophysiological results. However, functional status is frequently considered more as an outcome of a disease or a health condition. In physiotherapy treatment, the focus is on the improvement of function, therefore clinical outcome measures are based on assessment (7). This assessment includes assessing symptoms which are defined as being a departure from normal functioning or feelings that are noticed by a patient and can indicate the presence of disease or abnormality. For example, pain, dizziness, or level of confidence in balance control while performing activities, need to be assessed for patients through self-rated questionnaires and by health-related quality of life assessments (7).

In clinical settings, the scientific reasoning used to conceptualise the disease and disability of a patient and to then decide which treatment options may be offered to remediate problems, starts with diagnostic reasoning and procedural reasoning (7). In correlating the scientific reasoning with the ICF model, therapists engage with knowledge about the health condition of the person and the impact of this condition on body functions and structures and, therefore, on activity (7). Thus, scientific reasoning correlates to the ICF model in the health condition and the body functions and structures, and the potential impact on activity (7). In addition to narrative reasoning, which requires consideration about more than the organ systems and the disease process, an attempt to understand the experience from the patient's perspective is needed to tailor treatment specific to an individual's needs and preferences (7). This covers both the personal and environmental factors in the ICF model.

Therefore, the ICF model in rehabilitation is used not only to focus on the process to organize and plan medical therapy, but also for assessing functional status, the patient's needs, and the outcomes (3) which will enhance clinical reasoning. This includes both scientific and narrative reasoning. Assessment based on the ICF model thus depends on the limitation in activity and the present capacity of the patient and not only on the medical diagnosis. Overall, this will help in providing a common language and a framework for setting rehabilitation goals and undertaking specific treatment plans (3,491).

The selection of methodology was based on the research hypotheses, questions, aims, nature of the study, the study population, intervention and variables (492). The first experimental study (presented in Chapter 5) was observational clinical research to identify the capacity of walking at a functional level in ambulatory chronic stroke survivors compared to healthy controls and to assess the relationship between walking at a functional level (primary variables) and a set of factors (secondary variables) such as cognitive functions and psychological aspects for example balance confidence. Clinical outcome measures were used in the assessment of the primary and the secondary variables.

The second and third experimental studies were conducted to explore the feasibility of a novel telerehabilitation (HOLOBalance) system for balance training for older adults at risk of falls (Chapter 6) and ambulatory chronic stroke survivors (Chapter 7). The feasibility and accessibility of the system was assessed by a qualitative method including a semi-structured interview, in addition to validated questionnaires designed to evaluate the usability. The secondary aims were to identify trends of improvements in balance and functional walking, also, in cognitive and psychosocial aspects. Clinical outcome measures were conducted to assess the secondary aims. The selection of outcome measures used for the assessment in the following studies in this thesis was based on the validity and reliability and practicality in clinical practice which can be applied in physiotherapy clinics with no or minimum cost and prerequisites.

The assessment of walking at a functional level included assessing dynamic balance and functional gait, in order to identify the level of impairment in body structure and function, in addition to limitations in activity. It is important to recognise whether balance problems are due to body impairment such as vestibular dysfunction which can result in difficulty in maintaining balance with the eyes closed (40,493). The consequence of body impairment on activity limitation should be also assessed. For example, an inability to walk with a narrow base of support is important in recognising functional limitations for stroke survivors in the community, for instance walking between aisles. Furthermore, assessment of psychological status, such as levels of anxiety and depression, and the impact of environmental factors (such as walking in a dark area, or on uneven surfaces) on balance and functional gait, need to be included in the assessment.

For optimal walking at a functional level, there is a need for good balance in dynamic conditions and ability to perform functions while walking. More importantly, walking at a functional level requires cognitive function, more specifically attention and executive function which are needed to prioritise activity while walking (7). Nevertheless, cognitive impairments are common after stroke (195,494), therefore, there was a need to complete a cognition screening test and detailed cognitive function assessment. The following sections will explain the methods and materials more thoroughly.

4.2 Screening Procedures

4.2.1 A general screening questionnaire

A general screening questionnaire was used to check eligibility and clarify if a stroke survivor or healthy volunteers can participate in the studies (attached in Appendix 3). For example, it assesses whether there are other neurological conditions and cardiac problems, and if stroke survivors are able walk for 6-metres independently with or without the use of cane.

4.2.2 The Montreal Cognitive Assessment

The Montreal Cognitive Assessment MoCA (495) was used for cognitive screening in all the studies described in this thesis. The MoCA is a rapid screening tool for mild cognitive dysfunction and takes approximately 10 minutes to complete. The MoCA has better sensitivity in detecting mild cognitive impairments (496,497) other cognitive tests such as the Mini-Mental State Examination. Furthermore, the MoCA is a comprehensive tool to assess different cognitive domains including: visuospatial/executive function (tasks including: alternating trail-making, cube copying, clock drawing, naming animals), attention (tasks including: forward and backward digit span, tap your hand when you hear letter A, subtracting 7s from 100), language (tasks including: sentence repetition, letter fluency), abstraction (tasks including: similarities between a train and bicycle, watch and ruler), memory (tasks including: delayed verbal recall of 5 words) and orientation to time and place. A copy of the test is available in Appendix 4. The test has been validated for stroke survivors (495,498).

It has been recommended that the cut-off score for the MoCA to identify multidomain cognitive impairment is below 22 (<22/30) for stroke survivor participants and below 23 (<23/30) for healthy participants (495–497,499).

The cut-off score was selected according to recommendations of previous studies since a score of above 26 indicates no cognitive impairments and below 26 indicates mild impairments (500,501). To determine moderate cognitive impairments, a cohort of stroke survivors was tested at baseline and in a follow up period of 30 days with no treatment. Stroke survivors who had a score of 23 or above at the baseline showed improvements of up to 27, but participants who scored below 22 had no improvement, therefore a score of 22 was suggested as a cut off score for moderate cognitive impairments for stroke survivors (500,501). If the MoCA score is below the cut-off score, individuals will not continue with the questionnaires and physical tests.

4.2.3 The Motricity Index

The Motricity Index was used to assess lower limb motor function after stroke (502). The test requires participants to sit on a chair with no arms to manually assess the strength of ankle dorsiflexors, knee extensors and hip flexors. The outcome score is based on muscle strength and joint movement, for example the maximum score is given if a patient can perform a full range of motion against maximum manual resistance (502). The Motricity Index has a good reliability and acceptable validity (502–504). It has been used in previous studies to assess motor recovery after stroke (505). (A copy is present in Appendix 5).

4.2.4 The Physical Activity Scale for individuals with physical disabilities

The Physical Activity Scale for individuals with physical disabilities (506,507) is a 13-item questionnaire which quantifies physical activity participation in recreational, household, and occupational activities during the past 7 days. Each activity is assigned a specific metabolic equivalent (MET) value and the maximal PASIPD score is 199.5 MET hours/day, a higher score indicates better PA. Validity and reliability have been established for this measure (506,507). (A copy is presented in Appendix 6).

4.2.5 The Illness Perception Questionnaire-Revised

The Illness Perception Questionnaire-Revised (508) was used to identify participants' perception of stroke. Strokes can change perception which can alter survivors' abilities to process information. The questionnaire assesses perceptions with questions such as: "My illness has major consequences on my life" and "I have a clear picture or understanding of my condition". Higher scores (ranging from 0-24) indicate increased illness identity. (A copy is presented in Appendix 7).

4.2.6 The Situational Vertigo Questionnaire

The Situational Vertigo Questionnaire (94,509) consists of nineteen questions, which yield a normalised score between 0 (never) and 4 (always). This was used to assess how frequently symptoms of vertigo, dizziness, and/or unsteadiness are provoked or exacerbated in environments with visual-vestibular conflict or intense visual motion (e.g., supermarket aisles, watching moving scenes on the television, looking at a scrolling computer screen, traveling on escalators). The normalized score is obtained by dividing the total sum (range 0–76) by the total number of activities experienced - the higher the score the worse the symptoms (94,509). (A copy is presented in Appendix 8).

4.2.7 The Dizziness Handicap Inventory

The Dizziness Handicap Inventory is a 25-item self-assessment inventory was used to assess self-perceived handicap imposed by symptoms of dizziness (510). It has a high correlation with balance measures and gait performance (511). A score between 16-34 points indicates mild handicap, between 36-52 points indicates moderate handicap, and a score of 54 points and above indicates severe handicap (510). (A copy is presented in Appendix 15).

4.3 Assessment of physical, cognitive function and activity limitations

The methods of assessment of physical, cognitive function and activity limitation, in addition to psychological status and social participation which will be used in Chapters 5,6 and 7 is described below.

Although the most common clinical assessment for balance control is the Berg Balance Scale, it is limited to assessing balance from standing or walking for a short distance. Therefore, the Mini-Balance Evaluation System Test (Mini-BESTest) (294) was used to assess dynamic balance control in the current studies. Similarly, walking ability for stroke survivors can be determined by 10-metre walk test however it is limited to spatiotemporal parameters such as the pace of walking and it does not assess complex activity while walking. Therefore, the Functional Gait Assessment (FGA) (417) was used. The Dynamic Git Index (DGI) consists of tasks that can test complex walking; however, its sensitivity decreases with ambulatory individuals (50,297). The following paragraphs provide greater clarification for the Mini-BESTest and FGA.

4.3.1 The Mini Balance Evaluation Systems Test

The Mini Balance Evaluation Systems Test (Mini BESTest) (292) was used to assess dynamic balance. The Mini-BESTest includes 14 items which specifically assess anticipatory postural adjustments, reactive postural control, sensory organisation, and gait. It also includes the Timed Up and Go (TUG) test with a simultaneous cognitive task (countback in threes) while walking. The total score is a sum of all subtests out of 28 points. It has a good reliability and construct validity for stroke survivors (294), (A copy is presented in Appendix 9).

4.3.2 Functional Gait Assessment

Functional Gait Assessment (FGA) (295) was used to assess functions while walking, it includes a 10-item test to assess performance on complex, functional gait tasks (e.g., walking with horizontal or vertical head turns, stepping over obstacles) and has been validated for stroke survivors (512). It has been shown to reflect spatiotemporal gait parameters as well as the ability of stroke survivors to live independently (297). It has a good reliability and construct validity for stroke survivors (421). (A copy is presented in Appendix 10).

4.3.3 Assessment of cognitive functions

The Cambridge Neuropsychological Test Automated Battery (CANTAB tests available at https://www.cambridgecognition.com/cantab/), which is a semiautomated computer program that utilizes a touch screen technology and press pad, was used to assess cognitive function. The CANTAB core cognition battery is a validated cognitive assessment system for assessing multiple components of cognitive function, including attention, episodic memory, working memory, executive function and processing speed (513,514) (515). Each subject was comfortably seated at an approximate distance of 0.5 metres away from the screen pad monitor and asked to complete the CANTAB tests after instructions have been provided.

Validated CANTAB tests for stoke survivors and recommended by the CANTAB team are: For the attention domain, which is the ability to selectively select specific information whilst ignoring irrelevant information, and psychomotor and processing speed, the following tests were used:

4.3.3.1 Motor Screening Test

The Motor Screening Test was used to assess a participant’s general ability to understand and complete tasks and highlights if any sensorimotor or hearing impairments will have an impact on test performance. (Figure 4-3 illustrates the test).

Figure 4—3 Motor Screening Test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests).

4.3.3.2 Reaction Time Test

The Reaction Time Test was used to assess a person's mental and motor response speed. (Figure 4-4 illustrates the test).

Figure 4—4 Reaction Time Test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests).

4.3.3.3 Rapid Visual Information Processing Test

The Rapid Visual Information Processing Test was used to assess the ability to maintain visual attention (i.e., sustained attention) and continuous performance on a task. (Figure 4-5 illustrates the test).

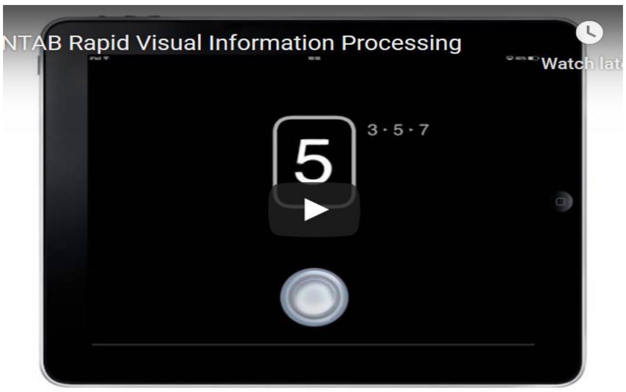


Figure 4—5 The Rapid Visual Information Test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests).

4.3.3.4 Paired Associated Learning Test

The Paired Associated Learning Test was used to assess visual memory and new learning. This test also assesses the executive function domain which is the cognitive domain that comprises high-level thinking and decision making. (Figure 4-6 illustrates the test).

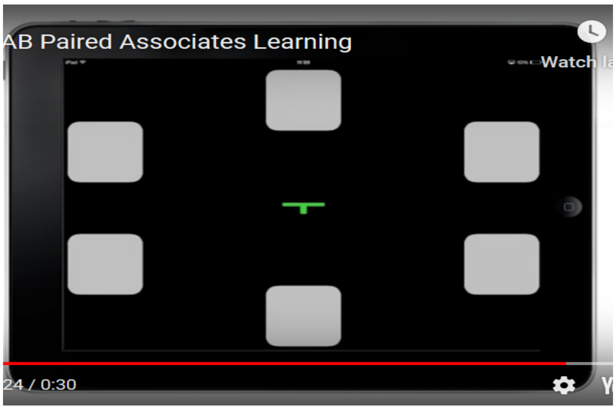


Figure 4—6 The Paired Associated Learning Test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests).

4.3.3.5 Spatial Working Memory Test

The Spatial Working Memory Test was used to assess participant's ability to retain and use visuospatial input. (Figure 4-7 illustrates the test).

Figure 4—7 The Spatial Working Memory Test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests)

Processing speed (latency) from the CANTAB suite was computed as an outcome measure. Further description for the CANTAB cognitive function tests, their aims and task procedures are available in Appendix 11.

4.3.4 Self-rated questionnaires to assess activity and participation limitations

4.3.4.1 The Environmental Analysis of Mobility Questionnaire

The Environmental Analysis of Mobility Questionnaire is a self-reported measure was used to determine frequency of encounter versus avoidance of environmental features affecting community walking in older adults. It has been used also for people with chronic stroke (263). The questionnaire examines 21 features of the physical environment grouped into 8 dimensions: distance (walking long distances, defined as ¼ mile or more), temporal (crossing a traffic light–controlled intersection and a busy street), terrain (escalator, curb, uneven surfaces, stairs), ambience (dark, rain, snow, and ice), physical load (heavy doors, carrying packages), postural transitions (reaching above shoulder height, below knee level, and beyond arm's length), attention (travel companion, unfamiliar locations, noisy and distracting environments), and density (crowded conditions).

The frequency of encounter and avoidance is reported using a 5-point ordinal scale (never, rarely, sometimes, often, and always). The total score for encounter items ranges from 1 (never encounter) to 5 (always encounter), similarly, total score for avoidance ranges from 1 (never avoid) to 5 (always avoid) (516). (A copy is presented in Appendix 12).

4.3.4.2 The Hospital Anxiety and Depression Scale

The Hospital Anxiety and Depression Scale (517) is a 14-item scale was used to assess non-somatic anxiety and depression symptoms. Scores range from 0-21 for each subscale with a score of ≥8 proposed for the identification of depression and anxiety in patients with different physical health conditions (518). When scores indicate abnormal symptoms of anxiety and/or depression (score ≥ 11), the participant was provided with information about how to self-refer to the local 'Improving Access to Psychological Therapy' service (https://www.england.nhs.uk/mental-health/adults/iapt/) as per normal clinical practice and if the participant preferred, a letter was provided to pass it to his/her general practice (GP). (A copy is presented in Appendix 13).

4.3.4.3 The Activities Specific Balance Confidence Scale

The Activities Specific Balance Confidence Scale (519) was used to assess the participant's confidence in performing 16 activities of daily living by rating the confidence from 0% (no confidence) to 100% (complete confidence) for each activity. It is the only questionnaire available to assess confidence on activity. The overall score was calculated by adding the individual item scores together: scores ≤67/100% indicate increased risk of falls (61). It has acceptable reliability and validity for stroke survivors (520). (A copy is presented in Appendix 14).

4.3.4.4 The Dizziness Handicap Inventory

The Dizziness Handicap Inventory is a 25-item self-assessment inventory was used to assess self-perceived handicap imposed by symptoms of dizziness (510). It has a high correlation with balance measures and gait performance (511). A score between 16-34 points indicates mild handicap, between 36-52 points indicates moderate handicap, and a score of 54 points and above indicates severe handicap (510). (A copy is presented in Appendix 15).

4.3.4.5 The Health-related Quality of Life Questionnaire

The European Quality of Life-5 Dimension (EQ-5D-5L)(521) is a generic measure of health status for clinical and economic appraisal that has validity for use in stroke survivors (522). The EQ-5D-5L is a descriptive system comprises of 5 dimensions (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression). Each dimension has 5 levels: no problems, slight problems, moderate problems, severe problems, and extreme problems. The EQ records the respondent's self-reported health on a 20 cm vertical, visual analogue scale with endpoints considered as 'the best health you can imagine' and 'the worst health you can imagine'. The participant was asked to mark an X on the scale to indicate "how your health is TODAY" (521).(A copy is presented in Appendix 16).

4.4 Additional assessment used for Study 2: Walking at a functional level in ambulatory stroke survivors in comparison to healthy controls (Chapter 5)

4.4.1 Subjective Visual Verticality Test

The test of Subjective Visual Verticality (SVV) perception assesses the contribution of vestibular function to the awareness of the sense of verticality (523). The Rod and Disc test was used to assess the SVV and to quantify the level of visual dependency (17,509,524), and has been used with stroke survivors in previous studies (523). A university laptop computer encrypted with a password was used to run the test for all participants.

Participants were seated in front of a computer in a darkened room. The visual stimulus consisted of a luminous white 6cm rod on a black background. The rod rotated 360 degrees in either direction about its midpoint in the central 11 degrees of the visual filed. Outside of this central zone, the viewing screen was filled with a collage of 220 off-white dots, each 8mm (1.5 degrees of visual field) in diameter, randomly distributed on a black background (presented in Figure 4-8).

Participants controlled the orientation of the rod with a roller mouse. They were instructed to align the rod to their perceived vertical (the SVV) under three conditions. In condition 1 (static), the collage of dots was stationary. In conditions 2 and 3 (dynamic), the collage rotated clockwise (CW) or counterclockwise (CCW), respectively, at 30 degrees/s. Four trials were completed in each condition, with conditions 2 and 3 presented in random order after condition one. During each trial, the rod was initially set randomly at ±40 degrees from vertical. The rod tilt for each trial was recorded as the difference in degrees between true vertical and the subjects' final placement of the rod for the SVV value, and the mean value for this difference from the four trials was calculated (525).

Visual Dependency (VD) was calculated as the mean difference between Subjective Visual Verticality (SVV) in CW/CCW and the static: VD= [(SVVCW-SVV static) + (SVVCCW-SVV static)]/2, a score of between ±2° is within normal range of VD (17,525). A score between 2°-4° indicates a minimum increase in the SVV and a score of > 4° indicates increased SVV (93,526).

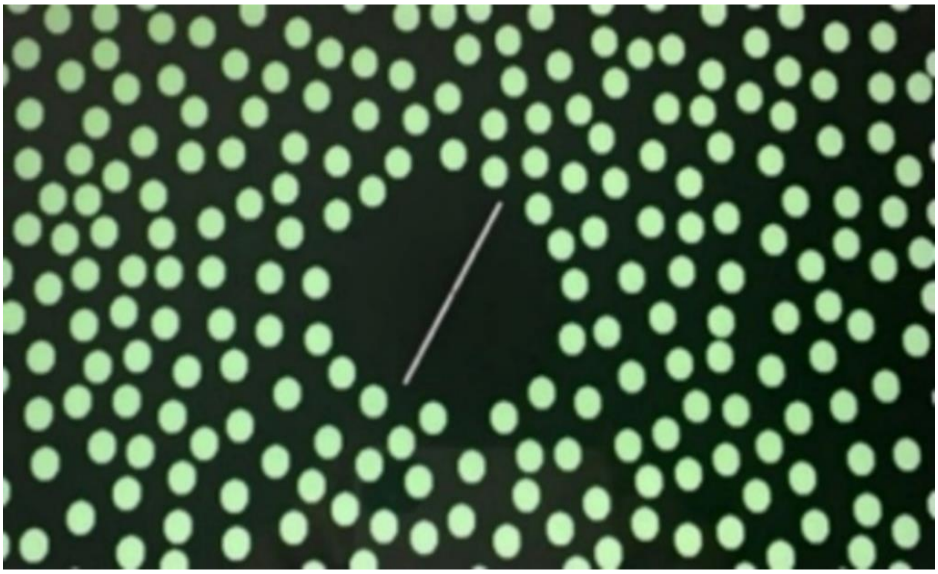


Figure 4—8 The Rod and Disc Test from a laptop screen.

4.4.2 The Pittsburgh Sleep Quality Index

The Pittsburgh Sleep Quality Index (527) was used to assess the quality of sleep. The index comprises seven component scores: subjective sleep quality, sleep latency, sleep duration habitual sleep efficiency, sleep disturbance, use of sleeping medication, and daytime dysfunction. The sleep component scores are summed to yield a total score ranging from 0-21, the higher total score (referred to as global score) indicating worse sleep quality. In distinguishing good and poor sleepers, a global Pittsburgh Sleep Quality Index score >5 yields a sensitivity of 89.6% and a specificity of 86.5% (527). (A copy is presented in Appendix 17).

4.4.3 The Epworth Sleepiness Scale

The Epworth Sleepiness Scale (528) was used to assess the daytime sleepiness. The scale is a validated and widely used questionnaire exploring daytime sleepiness (528). It consists of eight questions that are added together to obtain a single number, higher scores indicate a sleeping disorder. The reference range of 'normal' scores is 0-10 while scores of 11-24 represent increasing levels of 'excessive daytime sleepiness'. (A copy of the scale is presented in Appendix 18). Both the Pittsburgh Sleep Quality Index and the Epworth Sleepiness Scale have been used in stroke survivors (529,530).

4.4.4 Physical Activity level

Physical Activity (PA) level was assessed by the Axivity Band 3-Axis (AX3) logging accelerometer (531–533). The AX3 is a single tri-axial accelerometer-based wearable accelerometer. It weighs 11g, capturing triaxial acceleration data at 100 Hz with a dynamic range of ±8g and has been widely used in population-based studies to assess PA levels (531,532). The validity of the AX3 accelerometer for stroke survivors has been established previously (534). Stroke survivor participants were asked to wear the AX3 accelerometer on their non-paralysed wrist. This placement of AX3 accelerometer for stroke survivors has been validated in a previous study (535).

Additionally, healthy control participants were asked to wear the AX3 accelerometer on their non-dominant hand. Data collection started from the time of the assessment session and for 24 hours a day, for 7 days without taking it off. The AX3 accelerometer is waterproof and can therefore be worn in the shower and bath (536). The AX3 accelerometer does not track GPS and no information on location is recorded. Participants were asked to return the accelerometer via a prepaid envelope, after completing the wearing time. A guidance leaflet for the activity monitor was also provided to ensure consistent and accurate use of the accelerometer.

The data downloaded and analysed included the wear time and the cut-off points to determine the level of PA. Wear time window (epoch 24) for 7 consecutive days was selected for compliance, with a wear time of less than 6 days recorded as being non-compliant. The cut-off point is defined as the time which has been spent at a specific PA intensity, where each intensity band is categorized in units of Metabolic Equivalent of Task (MET), sedentary < 1.5 MET, light < 3 MET, moderate > 3 MET< 6 MET, vigorous > 6 MET (6,537). To determine the level of PA for both groups from the AX3 accelerometery, the average for 7 days with a cut-off point of 10 minutes was recorded.

4.5 Additional assessment used for Study 3 and Study 4 for the feasibility of the HOLOBalance system for balance training (Chapters 6 & 7)

An exit interview was used to assess the feasibility and acceptability of the HOLOBlance system. The following section will discuss the qualitative methodology used for the exit interviews. These were followed by additional tests for older adults at risk of falls.

4.5.1 Qualitative methodology approach for exit interviews

A qualitative approach involves analysing non-numerical data to understand the various aspects of a project, which helps explore underlying reasons, experiences, behaviours, motivations, and attitudes. Additionally, qualitative research enables the exploration of personal, social, and contextual factors that influence health outcomes, which in turn helps in the understanding of diverse health beliefs and practices and addressing comprehensive determinants of health in general (538,539).

A qualitative methodology is based on phenomenology (i.e., is the study of appearances of things, or things as they appear from experience), ethnography (i.e., participant-observation), grounded theory (i.e., generation of theory), and case study research each approach can offer unique insights (538,540). A qualitative methodology often involves techniques such as interviews, focus groups, and open-ended surveys to gather subjective insights (541). In feasibility studies, a qualitative methodology can be utilized to assess the viability of a project by delving into the perspectives and experiences of participants (542). This can include understanding their needs and concerns, identifying potential obstacles, and gaining insights into the social, cultural, and organisational context.

Qualitative techniques help feasibility studies to add a comprehensive understanding of contextual factors that may impact the success of a project. Recognizing and addressing these factors, which will help tailored the intervention to meet the needs of specific populations (542,543).

The process to generate qualitative data from the interviews includes a) open-ended questions to allow interviewees to express themselves freely to elicits richer, more detailed responses; b) active listening to pay close attention to the interviewee's responses and be prepared to ask follow-up questions to explore their experiences and perspectives in more depth; c) establishing rapport with interviewees to encourage them to share their thoughts more openly through empathy, and non-verbal cues; d). searching for detail and specific examples, or further explanations to help in understanding the interviewee’s experiences (541).

Thematic analysis based on an inductive approach was used to identify common themes and patterns within the qualitative data. Thematic analysis is considered a powerful method to help understand experiences, behaviours, or thoughts from an interview (544). Thematic analysis is a relatively flexible approach, making it suitable for a wide range of research questions and theoretical frameworks. It uses systematic process which can be easily applied and effectively provide clear and rich findings (541). The data from the semi-structured interviews was used to determine the themes based on the six steps for thematic analysis developed by Braun and Clarke (2017): familiarisation, coding, generating themes, reviewing themes, defining themes and reporting (545,546). The semi-structured interview used in studies 5 and 6 is available in Appendix 19.

4.5.2 Assessment of feasibility, acceptability, and usability of the HOLOBalance system

The following measures provide information on the usability and were collected from the active intervention (HOLOBalance/ HOLOBox) group in the final session of the treatment program (week 8).

4.5.2.1 The System Usability Scale

The System Usability Scale is a 10-item questionnaire that asks individuals to rate their experience of using the system on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) (547). An example from the scale include ‘I think that I would like to use this product regularly’(547). (A copy of the scale is presented in Appendix 20).

4.5.2.2 The User Experience Questionnaire

The User Experience Questionnaire is a 26-item self-report questionnaire to assess a person’s experience of using a product. Participants rate the product between two contrasting attributes (e.g., attractive vs unattractive) on a 7-point Likert scale, where zero represents neutral, 1 to 3 is positive and -1 to -3 is negative (548). (A copy of the scale is presented in Appendix 21).

4.5.2.3 The NASA Task Load Index

The NASA Task Load Index is a self-reported, multidimensional assessment tool which is widely used to rate perceived workload to assess a task, system, or other aspects of performance. The NASA TLX assesses workload on five 21-point visual analogue scales ranging from 0 (Very Low) to 21 (Very high) for task demands including mental demand, physical demand, and temporal demand (549). (A copy of the scale is presented in Appendix 22).

4.5.2.4 Adherence to exercise

Adherence to exercise was assessed to mean completing the exercises in the sessions from the HOLOBalance platform for the active group and from the exercise progress notes for the control group. The adherence to home exercise was assessed from the home exercise diary and these were collected weekly from week 1 to week 10.

4.5.3 CANTAB tests for older adults at risk of falls

In addition to the described CANTAB tests under section "4.3 Assessment of cognitive function", older adults at risk of falls participants in Study 3 presented in Chapter 6 completed the following CANTAB tests:

4.5.3.1 Match to Sample Visual Search test

This test was used to assess the attention domain and psychomotor speed for visual associative learning and memory. (Figure 4-9 illustrates the test).

Figure 4—9 Match to Sample Visual Search test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests).

4.5.3.2 Pattern Recognition Memory test

This test was used to assess the memory domain, specifically visual pattern recognition memory. (Figure 4-10 illustrates the test).

Figure 4—10 Pattern Recognition Memory test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests)

4.5.3.3 Delayed Matching to Sample test

This test was used to assess visual recognition memory and short-term visual memory. (Figure 4-11 illustrates the test).

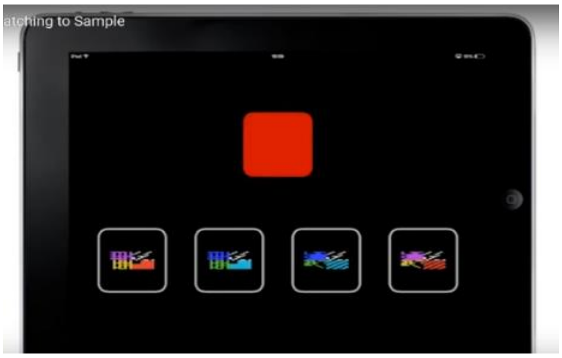


Figure 4—11 Delayed Matching to Sample test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests).

4.5.3.4 Multitasking test

The Multitasking test was used to assess executive function domain through testing participant's ability manage conflicting information. (Figure 4-12 illustrates the test).

Figure 4—12 Multitasking test from the Cambridge Neuropsychological Test Automated Battery (CANTAB tests).

4.5.4 Self-rated questionnaires to assess activity and participation limitations

4.5.4.1 The WHO Disability Assessment Schedule 2.0

The WHO Disability Assessment Schedule 2.0 provides a global measure of disability. It covers cognition (understanding & communicating); mobility (moving & getting around); self-care (hygiene, dressing, eating & staying alone); getting along interacting with other people; life activities (domestic responsibilities, leisure, work & school); participation (and joining in community activities). The rating is on a scale of 0 (no difficulty) to 4 (extreme difficulty or cannot do) (550). (A copy is available in Appendix 23).

4.5.4.2 The Falls Efficacy Scale International

The Falls Efficacy Scale International is a short, easy to administer tool to measure the level of individual concern regarding falling during social and physical activities inside and outside the home, and whether the individual can do an activity. The level of concern is measured on a four-point Likert scale (1=not at all to 4=very). It has excellent internal validity and test-retest reliability. Scores of >10 for the short form have been suggested as cut points for indicating high concern about falling (551). (A copy is available in Appendix 24).

4.5.4.3 The Rapid Assessment of Physical Activity

It is a 9-item, self-administered questionnaire developed to provide an easily administered way to assess levels of PA among adults older than 50 years. The Rapid Assessment of Physical Activity evaluates a wide range of PA levels, from sedentary to vigorous activity, as well as strength and flexibility training and takes 5-minutes to complete. It has adequate convergent validity and good criterion validity (552). (A copy is present in Appendix 25).

4.5.4.4 The Behavioural Regulation in Exercise Questionnaire

The Behavioural Regulation in Exercise Questionnaire is a 24-item questionnaire to assess motivation to exercise. Participants rated whether statements applied to themselves (or not) using a 5 point Likert scale ranging from 0 (Not true for me) to 4 (Very true for me) (553,554). (A copy is available in Appendix 26).

Table 4-1 presents a summary of assessments used in Study 2 (Chapter 5), Study 3 (Chapter 6) and Study 4 (Chapter 7).

Study 2 (Chapter 5) Walking at a functional level in ambulatory stroke survivors in comparison to healthy controls	
Primary outcomes	- Mini BESTest - FGA
Secondary outcomes	- Perception of visual vertical - CANTAB tests - The Activities Specific Balance Confidence Scale - Hospital Anxiety and Depression Scale - Environmental Analysis of Mobility Questionnaire - PA level was assessed by the AX3 accelerometer
Study 3 (Chapter 6) The feasibility of HOLOBalance system for balance training among older adults at risk of falls	
Primary outcomes	- Feasibility - Acceptability - Usability scales: The System Usability Scale, the User Experience Questionnaire, NASA Task Load Index. - Adherence rate
Secondary outcomes	- Mini BESTest - FGA - CANTAB tests - The Activities Specific Balance Confidence Scale - Hospital Anxiety and Depression Scale - WHO Disability Assessment Schedule 2.0 - Falls Efficacy Scale International - The Behavioural Regulation in Exercise Questionnaire
Study 4 (Chapter 7) The feasibility of HOLOBalance system for balance training among ambulatory stroke survivors	
Primary outcomes	- Semi-structured Exit Interview - Usability scales: The System Usability Scale, the User Experience Questionnaire, NASA Task Load Index. - Adherence rates to exercise
Secondary outcomes	- Mini BESTest - FGA - CANTAB tests - The Activities Specific Balance Confidence Scale - Hospital Anxiety and Depression Scale - WHO Disability Assessment Schedule 2.0 - Falls Efficacy Scale International - The Behavioural Regulation in Exercise Questionnaire - Health-related Quality of Life questionnaire - Environmental Analysis of Mobility Questionnaire (Encounter and Avoidance) - Physical Activity Scale for Individuals with Physical Disabilities - Dizziness Handicap Inventory

Table 4-1 A summary of assessments used in each study. The Mini Balance Evaluation Systems Test (Mini BESTest), Functional Gait Assessment (FGA), Cambridge Neuropsychological Test Automated Battery (CANTAB) tests.

4.6 Impact of COVID-19 on the methodology

The COVID-19 pandemic had a marked impact across society. The British Medical Association reported that, across the UK, the first wave of the COVID-19 pandemic was from February to September 2020. Extraordinary efforts were needed to staff the health services and again in the second wave from September 2020 to April 2021. After the first wave, the UK health services made considerable progress in restoring non-COVID related activity. However, suspension of services became necessary again during the second wave in order to cope with increased pressures on the health services and waiting lists drastically increased (72).

The third and fourth waves occurred from May 2021 to present (2023) where there has been increasing emphasis on the recovery of elective care. Yet the goals governments across the UK have set, have been extremely difficult for health services to meet without a costed, national, comprehensive workforce strategy. These goals focus on staff retention as well as training and recruitment (72).

Moreover, the COVID-19 pandemic had a huge impact on conventional work settings including universities (67). During the pandemic, both stroke survivors and older adults were classified as "vulnerable" (68). As such, during the lockdown period, physical contact between people was prohibited and when the restrictions were reduced there was a requirement to limit the number of participants each day to minimise physical contact (67).

For this project, prior to the COVID-19 pandemic, the initial plan for assessment was to include an aspect of neuroimaging with the functional Magnetic Resonance Imaging (fMRI) for stroke survivors to determine whether dynamic balance and functional gait are correlated with the brain's neural activity. The fMRI showed the changes in neural activities in the relative concentration of oxygen in local blood supply since oxygenated blood has different magnetic susceptibility relative to deoxygenated blood, thus the changes in the ratio of oxygenated/deoxygenated blood could be calculated (52). The presentation of the neuronal activity would help to determine whether there is a correlation with dynamic balance and functional gait in ambulatory stroke survivors with the stroke location and other possible factors. However, during the pandemic the priority for fMRI scanning was for urgent cases (555). Additionally, hospital access to people with chronic neurological conditions was postponed during the pandemic since patients were at risk of serious consequences from COVID-19 infection (556–558). Thus, this part of the project could not proceed as planned.

4.7 Potential biases in studies and ethics

Potential biases in studies could include selection bias at baseline, for example confounding in sampling which was based on convenient approach. In addition, performance bias such as the treatment provided to participants before the data collection was varied and not specified in the screening. Detection biases can occur as a result of timing and exposure to different variables. The assessor was not blinded in studies 2 and 4 for pre-intervention and post-intervention because of the limitations in funding. Additionally, biases in the assessment included the lack of more objective measurement for balance and gait for example with force plate system (559), or Vicon (560).

Potential biases in ethics might be related to selection bias which occurs when the participants included in the study are not representative of the broader population. It can affect the external validity of the research findings. Exclusion criteria, for example, stroke survivors with aphasia and with moderate or severe cognitive dysfunction were not included, because of the difficulty of performing the CANTAB cognitive tests, this limits the generalisability of the findings. In addition, because of lack of funding for an interpreter, participants were required to have a good English level.

Chapter 5: Factors associated with walking at a functional level in ambulatory chronic stroke survivors vs healthy adults.

5.1 Introduction

Mobility problems are among the most frequent and disabling effects of stroke (57). Mobilising safely in external environments requires significantly more than the ability to walk independently on level ground in a rehabilitation clinic or at home (561). Moreover, the limited ability of walking safely reduces participation in the community (251). In a previous qualitative study by Nanninga et al (2018), stroke survivors reported challenges when mobilising in different environments (561), and this in turn increases their risk of falls (76,77,562–564). In a cohort study of 144 community-dwelling ambulatory stroke survivors, the incidence rates of fall-related fractures reached 3 per 100 person/year, and falls were caused most often by losing balance while walking (565).

Ambulating safely at home and in the community requires the ability to walk at a functional level, including turning the head left and right to cross the road or walking while talking or carrying a shopping bag (i.e., dual-task walking) (15,16). Functional gait requires adaptation to behavioural task goals and environmental demands (566). A review by Balasubramanian et al (2014) developed a framework for the dimensions of walking in the community. This framework includes the ability 1) to negotiate obstacles in the environment, 2) walk on uneven surfaces to prevent a collision, 3) manoeuvre the entire body, such as walking around an obstacle, 4) be able to respond to ambient demands such as weather conditions, 5) adapt postural transitions such as bending down to pick up an object while walking or bear additional physical load such as when opening a heavy door, and 6) manage time constraints imposed on walking such as needing to walk quickly to cross a street (566).

Meanwhile, walking speed measured in a more controlled clinical setting (i.e., the 6-metre walk test) is commonly used as a predictor for walking in the community (564,567). These tests such as the 6-minute walk test measure distance in metres but do not provide information on a person's ability to perform any of the activities included in the community walking framework developed by Balasubramanian et al (2014). Thus, there is a need to assess walking at a functional level including tasks such as walking in narrow spaces or walking in dark areas (566). A study by Van Bloemendaal et al (2019) recruited 52 stroke survivors able to walk independently (mean gait speed 1.1 ± 0.4 metres/seconds) and identified that the functional gait (FGA) median score was 22 out of 30 points, which indicates limited functional walking ability (421). Furthermore, Tsang et al (2013) recruited 105 stroke survivors and the median score for the Mini-BESTest was 19 out of 28 points which indicates balance dysfunction and increased fall risk (294).

Walking at a functional level for stroke survivors requires adequate balance control in dynamic and challenging situations (55,568) which is affected by multiple factors including motor impairment recovery, spasticity, and joint stability, especially in the knee and ankle joints (40,41). In addition to the aforementioned components for balance control, previous studies in stroke survivors reported that balance control was associated with over-reliance on visual input (i.e., visual dependency), as opposed to proprioceptive and vestibular inputs for spatial orientation and postural control (94,96,569). Patients with visual dependency may experience dizziness, disorientation, and/or unsteadiness in situations involving visual-vestibular conflict (for example, walking down supermarket aisles) or intense visual motion such as watching wide-screen movies).

It has been suggested that visual dependency indicates an incorrect sensory-reweighting process (570) where preponderance is given to visual input, even when incorrect, despite normal vestibular and proprioceptive cues (571). It has been hypothesised that visual dependency occurs as a compensatory adaptation to balance deficits after stroke (11,12,91), and such visual dependency has been identified as a contributor to balance problems in stroke survivors (11,12,89–91). Multiple studies have identified that visual dependency is associated with increased postural instability and fall risk (94,572,573). Bonan et al (2013) found increased postural sway in approximately 65% of stroke survivors in the subacute stage during exposure to visual motion stimuli indicating an inability to adapt in an environment with increased visual stimuli (91). The association between visual dependency and balance control, and functional gait in chronic stroke survivors remains unclear and one of the aims of this study is to identify if there is a relationship between visual dependency, dynamic balance and functional gait in ambulatory chronic stroke survivors.

Furthermore, previous studies have reported a relationship between stroke survivors' ability to walk in the community and cognitive function (205). With cognitive impairment and depression associated with increased fall rates in this population (563), cognitive function, specifically executive function and attention are important in assessing risks and decision making. Both of these are required to allocate cognitive demands and motor tasks for complicated motor tasks, for example when crossing a busy road (205).

In healthy subjects, during DT walking, young adults exhibited a more effective utilisation of prefrontal resources (achieved by higher recruitment) and better task performance than older adults (574). Meanwhile, study by Chatterjee et al (2019) of 33 stroke survivors found that during DT walking, there was lower prefrontal recruitment, consistent with a low recruitment ceiling effect in the prefrontal lobe, which indicates that poor cognitive function predicts lower DT performance (575). Cognitive function in Chatterjee et al's (2019) study was as assessed by the Mini-Mental State Examination, however, there is a need to assess cognitive functions with more detailed assessment and explore the relationship between cognitive functions and dynamic balance and functional walking.

Previous studies have also reported an association between community walking and balance self-efficacy (218,576). Stroke survivors with lower self-efficacy and lower cognitive ability take fewer steps per day (247,577). In these studies, though walking is assessed by walking speed only, there is a need to include more comprehensive tests for walking at a functional level in order to identify more optimal interventions.

Psychological symptoms such as anxiety and depression (578,579) are common after a stroke. A systematic review by Rafsten et al (2018) of 31 studies (13,756 stroke survivors) found that the prevalence of anxiety disorders among stroke survivors was 29.3% (95% confidence interval 24.8-33.8%) (580). Additionally, anxiety after stroke was found to be associated with poor quality of life (581), and decreased functional activity (i.e., the Barthel Index for activities of daily living) (582), with similar findings for depression (583,584).

Moreover, stroke survivors with increased anxiety and depression can have an increased perception of illness (585), and poor quality of sleep (230). All, in turn, can lead to decreased functional activity (586), promote social isolation and sedentary behaviours (587), and thus reduce quality of life (588). Meanwhile, health-related quality of life has been shown to be strongly associated with balance and the walking distance (589). The association between walking at a functional level and psychosocial variables needs further investigation for ambulatory chronic stroke survivors.

Moreover, decreased functional walking can increase sedentary life. Reduced levels of physical activity (PA) have been reported in ambulatory stroke survivors compared to age-matched healthy controls (206). A meta-analysis of studies identified that the average steps per day for 1105 stroke survivors was 4355 (95% CI: 3210.4 to 5499.9), which is below the average for a healthy elderly population (6000 steps/day) (56). Decreased PA levels accordingly decrease community engagement (206). Previous studies have shown that PA level was significantly correlated with balance control (590), walking speed, distance, and ability to go up and down stairs (591), but the association between PA and walking at a functional level remained undetermined.

Current physiotherapy interventions for balance and mobility commonly focus on a combination of sit-to-stand with walking, standing balance, and walking practice tests (36,592). The James Lind Alliance Priority Setting Partnership identified that the need for the best treatments to improve balance, gait, and mobility are in the top ten stroke research priorities (49). To provide optimal tailored physiotherapy treatment to improve dynamic balance and functional walking there is a need to identify the association between walking at a functional level and multiple factors indicated above.

5.1.1 Study objectives and hypothesis

The primary objective is to identify if walking at a functional level is associated with SVV, cognitive function, balance confidence, environmental demands, quality of life, quality of sleep, and the level of PA in ambulatory chronic stroke survivors in comparison to healthy adults. The hypothesis is that the factors associated with dynamic balance and functional gait levels for stroke survivors will be visual dependency, and specific cognitive function domains, while for healthy controls age, depression, and balance confidence will be the main factors.

5.2 Methods

5.2.1 Study design and participant recruitment

This is a cross-sectional pilot correlation study. The study protocol was approved by the King's College Research Ethics Committee (ID: 21866) available in Appendix 27. All study procedures were in accordance with the Declaration of Helsinki (593). Written informed consent was obtained from all participants after they had received information about the study and given opportunities to ask questions about study processes. Participants choose either to undergo testing in a single visit or over two separate visits at the research laboratories of the Centre for Human and Applied Physiological Sciences, Guy's campus, King's College London (KCL). Recruitment and completion of testing for assessment took 12 months. The schematic diagram of the trial design, procedures, and data collection can be seen in Figure 5-1.

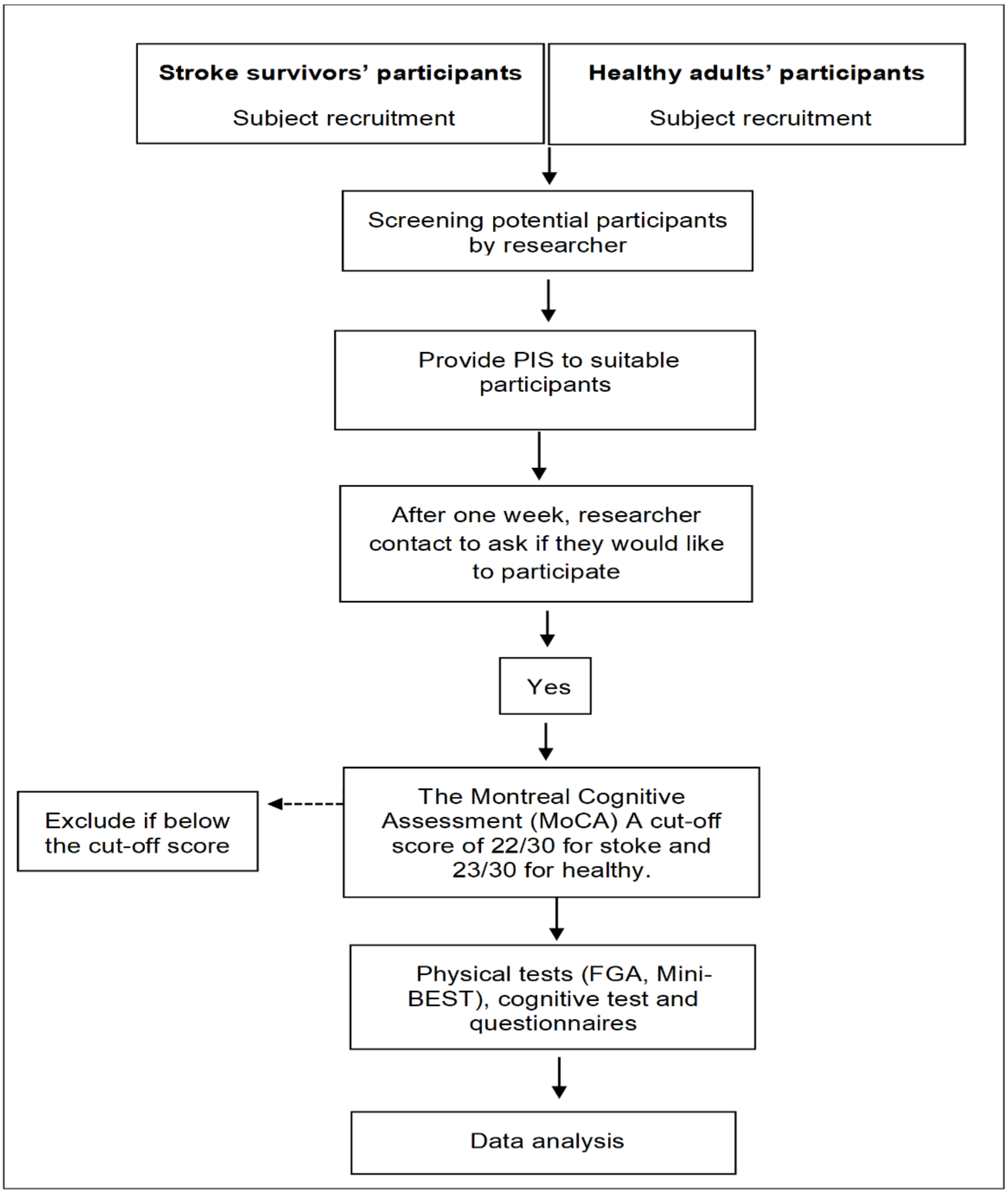


Figure 5—1 Schematic diagram of study design, procedures, and data collection. Participant Information Sheet (PIS).

5.2.2 Eligibility criteria

5.2.2.1 Stroke survivors

Participants in the stroke survivors' group were recruited through advertisements in the newsletters of various charitable bodies such as Stroke Association, Different Strokes, local community support groups and by contacting relevant charity staff members and support group organisers/leaders through email.

The MoCA (495) was used for the cognitive screening. More details are provided in Chapter 4 (General Methodology), under the section "4.3 Assessment of physical, cognitive function and activity limitation".

Inclusion criteria for stroke participants were individuals above 18 years old; who had had a stroke affecting the brainstem/cerebellum or middle cerebral artery; more than 3 months since stroke incidence; and were able to walk independently in the community with or without the use of a stick.

Individuals with diagnosis of other neurological conditions (other than stroke, i.e. diabetic neuropathy, Parkinson's); unstable cardio-respiratory disease; severe visual field deficit (i.e. homonymous hemianopia); cognitive dysfunction MoCA <22/30 (496); dementia; significant Pusher's syndrome still present at 3 months post-stroke; visuospatial disorder as assessed by the Star cancellation test (171); lack of a good grasp of written/spoken English (because of the questionnaires and cognitive tests that were to be used) and lack of funding for an interpreter, were excluded from the study.

5.2.2.2 Healthy Participants

Independently mobile, healthy participants were also recruited from the community by contacting people who had participated in previous studies and who agreed to be contacted for further research via their emails. In addition, posters were put up within the local community to recruit further participants. Inclusion criteria were that participants should be above 18 years old; and able to independently walk in the community with or without the use of a stick.

Exclusion criteria, chosen due to their potential impact on functional gait, were neurological conditions; unstable cardio-respiratory disease; severe visual problems; MoCA <23/30 (496); and/or lack of a good grasp of written/spoken English.

Recruitment occurred during the lockdown period for COVID-19. As a result, healthy controls were able to participate and attend an assessment session, with appropriate College-wide precautions and safety measures, before being able to recruit stroke survivors. As a result of the Covid-19 pandemic as well as the time limitations to complete the study within the PhD period, recruitment of stroke survivors was more challenging. Consequently, it was not possible to regulate the age and gender variables for the two groups.

5.2.3 Study Procedure

5.2.3.1 Screening

A screening log of all participants assessed for eligibility for enrolment into the study was completed. The screening log retained pseudo-anonymised data on the date the person was assessed, their gender, reason for exclusion, and eligibility for enrolment. For cognitive function, the MoCA (495) was used. Further explanation may be found in Chapter 4 (General Methodology) under the section "4.2 Screening Procedure"

The Motricity Index was used to determine lower limb functional motor recovery in stroke survivors. Similarly, the Illness Perception Questionnaire-Revised (508) was used to assess participants' perception of stroke. The Situational Vertigo Questionnaire (94,509) and the Dizziness Handicap Inventory (510) were used to assess visual induced dizziness symptoms and any perceived handicap from dizziness symptoms, respectively. The level of physical activity (PA) was screened before the use of AX3 accelerometery by the Physical Activity Scale for Individuals with Physical Disabilities (506,507). All tests were discussed in Chapter 4 (General Methodology) under the section "4.2 Screening Procedure".

5.2.4 Statistical analysis

Data analysis was conducted using statistical tests and techniques, using SPSS 25 (IBM Inc.), and for the graphs, Prism 8 (GraphPad Software, Inc.). Normality of data distribution was tested with the Shapiro-Wilk test, histogram, and Q-Q plots. Normally distributed data are presented as mean ± Standard Deviation (SD), and non-normally distributed data as medians and percentiles. A sample size calculation was not required as this is a pilot study (594).

The results indicated that data from the Functional Gait Assessment (FGA) for stroke survivors were normally distributed ($p > 0.21$) but for the FGA in healthy controls ($p < 0.03$) and other variables were not normally distributed. Figures 5-2 and 5-3 shows the Q-Q plot for the data distribution of FGA in stroke survivors and healthy controls, respectively. The scores for SVV for all conditions were normally distributed in both groups, except for the dynamic condition in the counterclockwise direction for the healthy controls.

Non-parametric statistical tests were used because of the small sample size and non-normal data distribution. The non-parametric tests are based on assumptions about the parameters of the population distribution from which the sample was drawn, thus it is considered less powerful than the parametric tests (595). The Mann-Whitney U test was performed to examine how demographic data and the primary outcomes (i.e., dynamic balance (Mini-BESTest), and functional gait (FGA)) differed between the study groups. To examine the difference between the study groups in secondary outcomes (i.e., SVV, cognitive CANTAB tests, and subjective variables), the Mann-Whitney U test was used for continuous data and the Fisher's test was used for categorical data.

Linear regression analysis was not performed due to the small sample size. Previous literature suggests a sample size of 50 subjects for each group is required to perform linear regression (232). Additionally, the data was not normally distributed. Therefore, the Spearman's rank-order correlation (r_s) for non-parametric tests was selected to identify the association between primary and secondary variables for each group.

The Spearman's rank-order correlations (r_s) were performed for the association between walking at a functional level (i.e., dynamic balance (Mini-BESTest), and functional gait (FGA)) and secondary outcomes (i.e., SVV, cognitive CANTAB tests, and subjective variables) when the scores for stroke survivor participants are different to the scores from healthy controls. When the scores of secondary outcomes from the stroke survivor participants are within a normal range and no different from the scores from healthy controls, correlation tests were not completed.

In addition, as multiple comparisons can increase the likelihood of Type I errors (596), it is important to adjust p-values to control for such errors. To account for multiple comparisons, a Bonferroni correction was applied. The corrected alpha level was calculated by dividing the desired overall alpha level (0.05) by the number of tests performed (40 tests), resulting in a new corrected alpha level of $p < 0.001$. Only significant associations will be presented after Bonferroni correction $p < 0.001$.

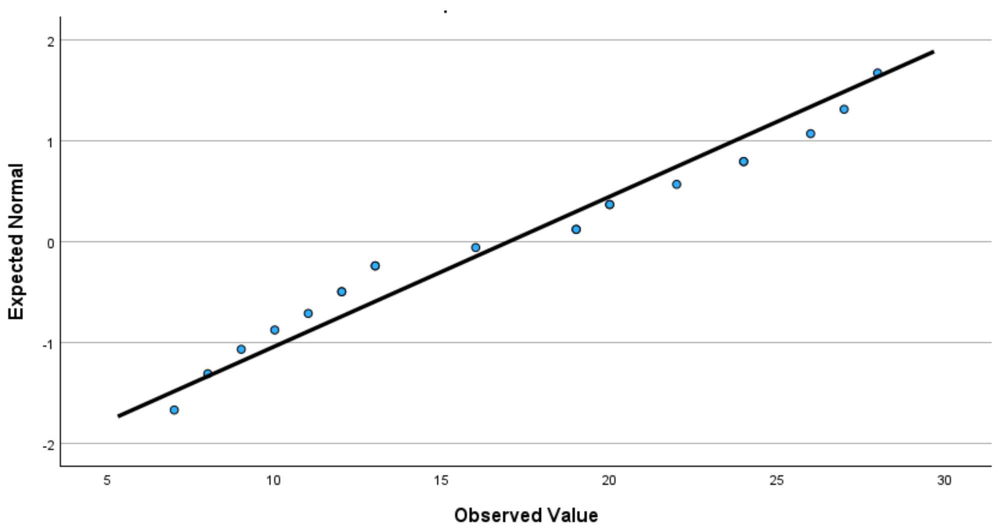


Figure 5—2 Q-Q plot of Functional Gait Assessment (FGA) in stroke survivors.

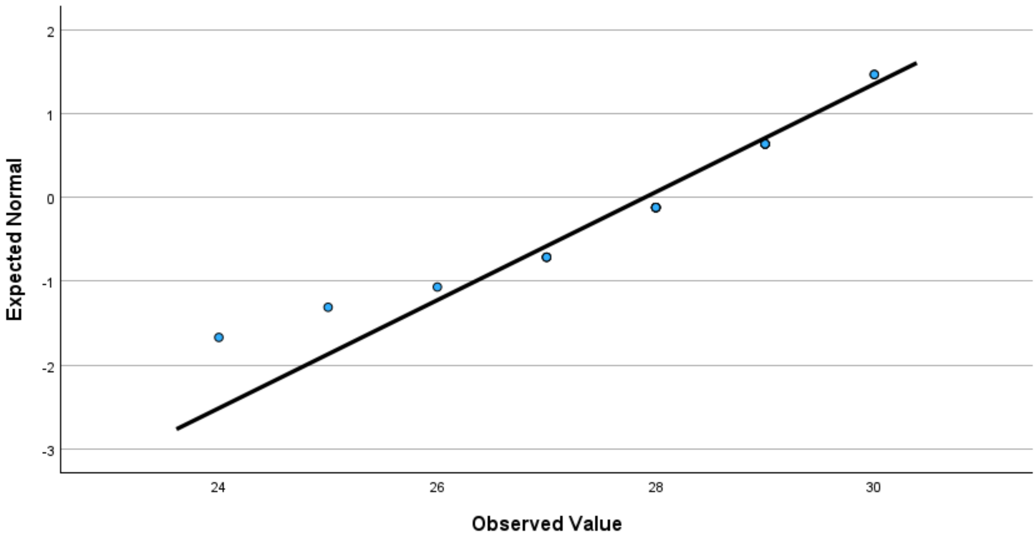


Figure 5—3 Q-Q plot of Functional Gait Assessment (FGA) in healthy controls.

5.3 Results

Twenty stroke survivors and 20 healthy participants were recruited between October 2021 and September 2022. No participant withdrew from the study after consent, and no deviation from the protocol was recorded. Participant characteristics are demonstrated below (Table 5-1). No significant between-group differences were noted for age and gender. All stroke survivor participants had a stroke > 1 year prior to taking part in the study.

In stroke survivors, the median score for lower limb functional motor recovery as assessed by the Motricity Index was 64 out of 100, (i.e., scores closer to 100 indicates better functional motor recovery). The Physical Activity Scale for Individuals with Physical Disability shows that the range was 101-520 (higher scores indicate better physical activity) (Table 5-2). The median scores of the Illness Perception Questionnaire-Revised for all items were below 40 which indicates no increased (i.e. no abnormal) illness perception was reported (Table 5-3). No abnormal scores for vertigo and dizziness were found in either group.

Variable	**Stroke survivors' group (n= 20)**	**Healthy controls (n= 20)**
Mean age (range)	60 (42-75)	64 (40-80)
Gender n (%)		
Female	14 (70%)	12 (60%)
Male	6 (30%)	8 (40%)
Mean stroke duration (range)	7.45 (1-21) years	NA
Hemiparesis side n (%)		
Left	12 (60%)	NA
Right	6 (30%)	
Non	2 (10%)	
Type of stroke n (%)		
Hemispheric lesion	19 (95%)	NA
Cerebellar lesion	1 (5%)	

Table 5-1 Stroke survivors and healthy controls participant characteristics.

	Motricity Index	Physical Activity Scale for Individuals with Physical Disability
Median	64	177
Range	43-100	101-520
Percentiles 25 75	58 84	126 425

Table 5-2 Median, range, and percentiles of Motricity Index and Physical Activity Scale for Individuals with Physical Disability, for stroke survivors (n=20).

	Median	Range	Percentiles 25 75
IPQ-R Timeline	18	12-25	16 20
IPQ-R Timeline cycle	11	4-20	8 13
IPQ-R Consequences	37	21-54	32 44
IPQ-R Personal control	19	11-31	16 21
IPQ-R Treatment control	8	3-12	7 9
IPQ-R Illness coherence	14	9-20	12 17
IPQ-R Emotional representations	28	9-36	24 32

Table 5-3 Median, range, and percentiles of Illness Perception Questionnaire- Revised (IPQ-R) items for stroke survivors (n=20).

5.3.1 Walking at a functional level

Table 5-4 and Table 5-5 show individual scores, mean ± standard deviation, median, range, and percentiles of the Mini-BESTest and FGA, respectively. Significant between-group differences were observed for both the Mini-BESTest and FGA. Mini-BESTest scores for stroke survivors (mean rank = 13.03) were significantly lower compared to healthy controls (mean rank = 27.98), U = 50.5, z = -4.07, (p < 0.001) (Figure 5-4). Similarly, FGA scores for stroke survivors (mean rank = 11.35) were significantly lower than for healthy controls (mean rank = 29.65), U = 50.5, z = -4.07, (p < 0.001) (Figure 5-5).

No association was noted between balance and functional gait, and age and gender in the stroke survivors' group and in the healthy controls. The association between dynamic balance and functional gait, with SVV, cognitive function, and subjective symptoms variables are presented in the following sections.

Mini-BESTest scores	Stroke survivors' group (n= 20)	Healthy controls (n= 20)
	27	28
	26	28
	21	26
	22	26
	17	27
	27	22
	23	27
	11	28
	22	26
	19	28
	7	27
	20	25
	15	25
	26	27
	14	27
	15	27
	16	22
	9	21
	8	25
	11	25
Mean ±SD	17.80 ±6	25.85 ±2.08
Median	18	26.50
Min- Max	7-27	21-28
Percentiles 25	11.75	25
75	22.75	27

Table 5-4 Stroke survivors and healthy controls individual scores, mean ± Standard Deviation (x̄ ±SD), median, range and percentiles scores for the Mini-Balance Evaluation Test (Mini-BESTest), maximum score is 28 points.

FGA scores	**Stroke survivors' group** (n= 20)	**Healthy controls** (n= 20)
	28	30
	24	30
	19	28
	22	27
	13	28
	27	25
	24	28
	12	29
	20	27
	20	29
	8	28
	19	26
	12	27
	26	29
	13	29
	11	29
	16	24
	7	28
	9	29
	10	28
Mean ±SD	17 ±7	28 ± 2
Median	17.5	28
Min- Max	7-28	24-30
Percentiles 25	11.25	27
75	23.50	29

Table 5-5 Stroke survivors and healthy controls individual scores, mean ± Standard Deviation ($\bar{x}$ ±SD), median, range and percentiles scores for the Functional Gait Assessment (FGA), maximum score is 30 points.

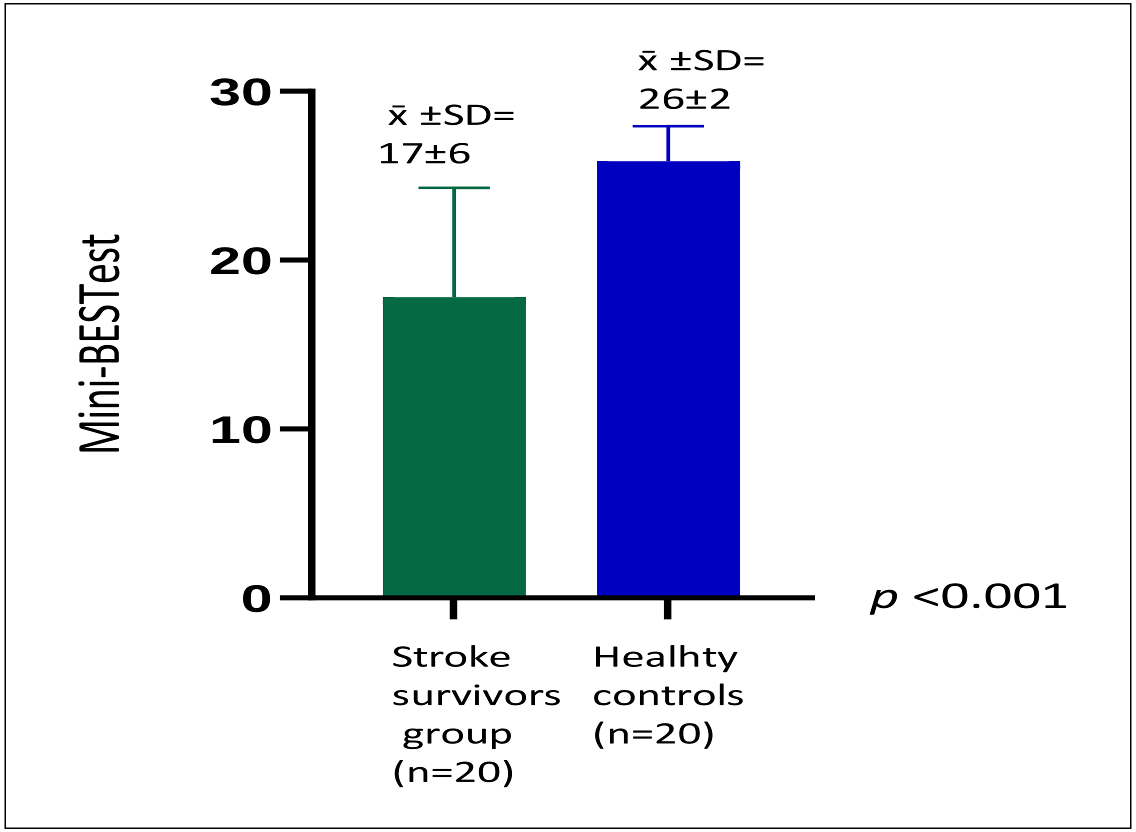


Figure 5—4 Mean and Standard Deviation (x̄ ±SD) for the Mini-Balance Evaluation System (Mini-BESTest) showed a significant difference between groups.

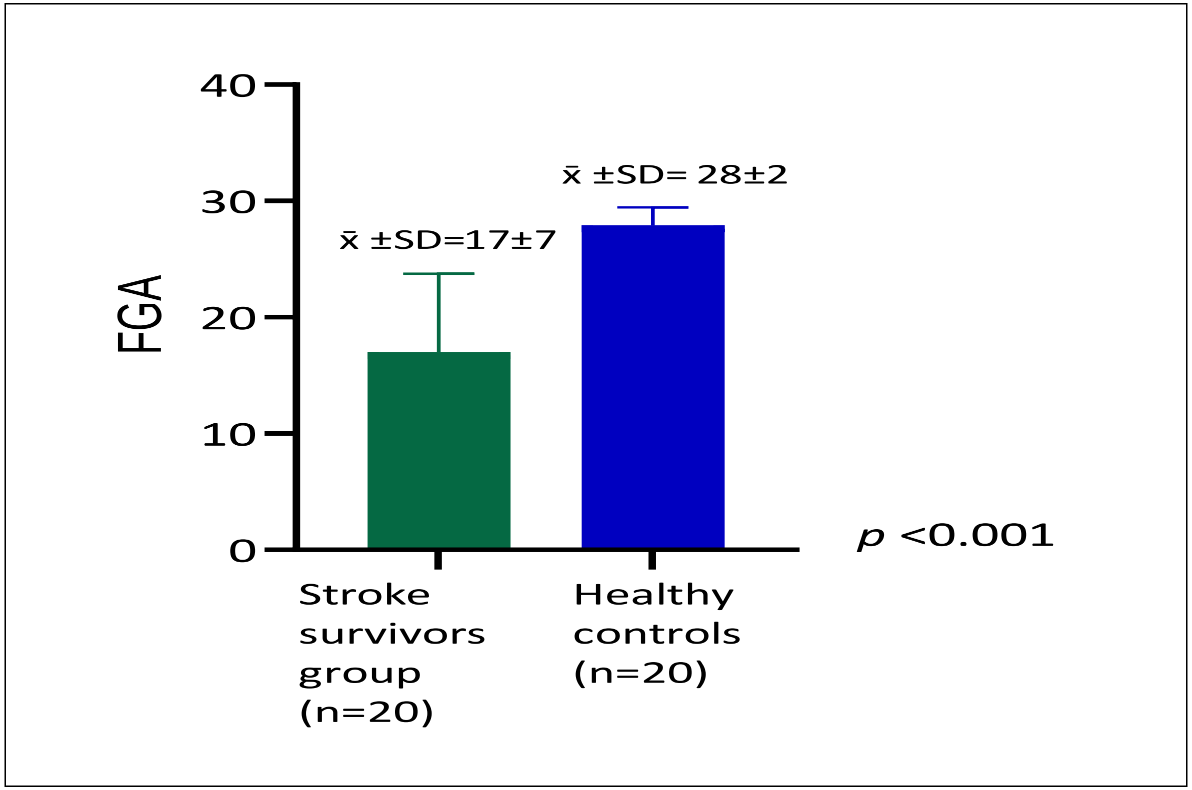


Figure 5—5 Mean and Standard Deviation (x̄ ±SD) for the Functional Gait assessment (FGA) showed a significance difference between groups.

5.3.2 Subjective Visual Verticality

All stroke survivors completed Subjective Visual Verticality (SVV) tests by the Rod and Disc test for the static condition; however, one stroke survivor participant had to stop and did not complete the dynamic condition. All healthy participants completed all tests.

Ninety percent of both the stroke survivors and healthy controls had a normal SVV score for the static condition (Table 5-6). However, in the dynamic condition CW and CCW directions only 45% of stroke survivors had normal SVV, while 65% of healthy controls had normal SVV in the dynamic CW condition and 40% in the dynamic CCW condition. Two stroke survivors had increased SVV of 5.1-6° in the dynamic CW condition, and one stroke survivor had increased SVV of 5.1-6° in the dynamic CCW condition. No healthy participants had an increased SVV of 5.1-6°.

Table 5-7 shows the mean of SVV with ±SD in the stroke survivors' group which was 0.39 ± 1.74◦ for the static background, (i.e., within the normal range). In the dynamic CW condition, visual rotation in the SVV was 1.28 ± 3◦, and in the dynamic CCW the SVV was -2.25 ± 1.79◦ (positive values indicate CW bias, and negative values CCW bias). In both dynamic directions an increased SVV is noted, but the level of visual dependency is within a normal range (visual dependency= -0.87° CCW bias). In the healthy controls, SVV was -0.27 ± 1.16◦ for the static background, 0.86 ± 1.78◦ for the dynamic CW, and -1.70 ±1.71◦ for the dynamic CCW. No difference was noted between stroke survivors and healthy controls in all SVV conditions.

The Rod and Disc test condition	**Static**			**Dynamic clockwise**					**Dynamic counter-clockwise**				
Degrees of SVV	0-2°	2.1°-4°	4.1°-5°	0-2°	2.1°-3°	3.1°-4°	4.1°-5°	5.1°-6°	0-2°	2.1°-3°	3.1°-4°	4.1°-5°	5.1°-6°
Stroke survivors (n=20)	18 (90%)	2 (10%)	0	9 (45%)	3 (15%)	2 (10%)	3 (15%)	2 (10%)	9 (45%)	2 (10%)	5 (25%)	2 (10%)	1 (5%)
Healthy controls (n=20)	18 (90%)	2 (10%)	0	13 (65%)	6 (30%)	0	1 (5%)	0	8 (40%)	8 (40%)	4 (20%)	0	0

Table 5-6 Frequency of Subjective Visual Vertical (SVV) and percentages (%) of static, dynamic clockwise, and dynamic counter-clockwise conditions in stroke survivors and healthy controls from the Rod and Disc Test.

The Rod and Disc test condition	Stroke survivors (n=20)	Healthy controls (n=20)
Static		
Mean ±SD Median	0.39 ± 1.74◦ 0.9◦	-0.27 ± 1.16◦ 0◦
Dynamic clockwise		
Mean ±SD Median	1.28 ± 3◦ 2◦	0.86 ± 1.78◦ 1.4◦
Dynamic counter-clockwise		
Mean ±SD Median	-2.25 ± 1.79◦ -2.5◦	-1.70 ±1.71◦ - 2◦

Table 5-7 Mean ±SD and median of the Subjective Visual Vertical (SVV) scores for static, dynamic clockwise, and dynamic counter-clockwise conditions in stroke survivors and healthy controls from the Rod and Disc Test.

5.3.3 Cognitive functions

Descriptive data for the cognitive tests are presented in Table 5-8. A significant between-group difference only for three CANTAB cognitive tests was observed. Mean rank scores for the motor screening task were higher for stroke survivors (mean rank= 23) vs. healthy controls (mean rank = 13), with U=58, z= -2.93, and *p*< 0.004. Similarly, mean rank scores for the reaction time task for stroke survivors (mean rank =23) were higher than for healthy controls (mean rank= 13), U= 52, z= -3.14, *p*< 0.002. Mean rank scores for rapid visual information processing were higher in stroke survivors (mean rank= 22) than for healthy controls (mean rank= 14), U=73, z= -2.41, *p*< 0.01. No difference was noted between groups in the other cognitive CANTAB tests (i.e., match to sample visual search test and the paired associated learning test).

No association was noted between the Mini-BESTest or FGA and the cognitive CANTAB tests (motor screening task, reaction time task, rapid visual information processing) in either group.

Cognitive CANTAB tests	Stroke survivors			Healthy controls		
	Median	Range	Percentiles 25 75	Median	Range	Percentiles 25 75
Motor screening task	1046	583-2288	885 1352	757	646-1529	689 859
Match to sample visual search	3954	1900-8592	2847 6006	3554	2260-7673	2867 3809
Paired associated learning	18	2-66	11 42	14	2-64	8 40
Reaction time task	466	380-605	415 493	398	303-489	357 423
Rapid visual information process	556	382-1005	508 672	475	321-759	421 577

Table 5-8 Median, range, percentiles, of the Cambridge Neuropsychological Test Automated Battery (CANTAB) cognitive tests for stroke survivors and healthy controls. All tests are measured in seconds, except the paired associated learning test was measured by the number of incorrect choices.

5.3.4 Self-rated questionnaires for the subjective variables

Descriptive data for subjective questionnaires are presented in Table 5-9. A significant between-group difference was observed in Activity-specific Balance Confidence scores, which were lower (i.e., worse) for stroke survivors (mean rank= 12) than for healthy controls (mean rank = 28), U= 39, z= -4.34, $p< 0.001$.

A strong positive association was observed between the Mini-BESTest and the Activities-specific Balance Confidence scale in the stroke survivors' group, where higher (i.e., better) Mini-BESTest scores were associated with increased (i.e., better) Activity-specific Balance Confidence scores, $r_s= 0.72$, $p < 0.001$, (Figure 5-6). Similarly, for the FGA and Activities-specific Balance Confidence scale, higher (i.e., better) FGA scores were associated with increased (i.e., better) Activity-specific Balance Confidence scores, $r_s= 0.75$, $p < 0.001$, Figure 5-7. No associations between the Mini-BESTest or FGA and the Activity-specific Balance Confidence scores in healthy controls.

No difference between-group for the other subjective variables (the Hospital Anxiety and Depression scale, the Environmental Analysis of Mobility Questionnaire – encounter and avoidance, Health-related Quality of Life Questionnaire, the Pittsburgh Sleep Quality Index, and the Epworth Sleepiness Scale).

Self-rated questionnaires for the subjective variables	Stroke survivors			Healthy controls		
	Median	Range	Percentiles 25 75	Median	Range	Percentiles 25 75
Activities-specific Balance Confidence Scale	60	16-97	30 82	60	73-100	30 82
Hospital Anxiety and Depression Scale - Depression	7	1-14	3.25 10	1	0-4	0 3
Hospital Anxiety and Depression Scale – Anxiety	8	0-16	6.25 10.5	2	0-10	0.25 4
Health-related Quality of Life Questionnaire (EUQ-5) percent	70	30-90	52 87	85	70-100	80 98
Environmental Analysis of Mobility Questionnaire-Encounter	2	1-3	1 2	2	2-2	2 3
Environmental Analysis of Mobility Questionnaire- Avoidance	1.5	1-3	1 2	1	0-1	0 1
Pittsburgh Sleep Quality Index	7	2-13	5 9	5	2-10	4 7
Epworth Sleepiness Scale	3.5	0-10	1 8	5	0-12	2 8

Table 5-9 Median, range and percentiles of Activities-specific Balance Confidence Scale, Hospital Anxiety and Depression Scale - for Depression, Hospital Anxiety and Depression Scale - for Anxiety, Health-related Quality of Life Questionnaire (EUQ-5), Environmental Analysis of Mobility Questionnaire (Encounter and Avoidance), Pittsburgh Sleep Quality Index, Epworth Sleepiness Scale for stroke survivors and healthy controls.

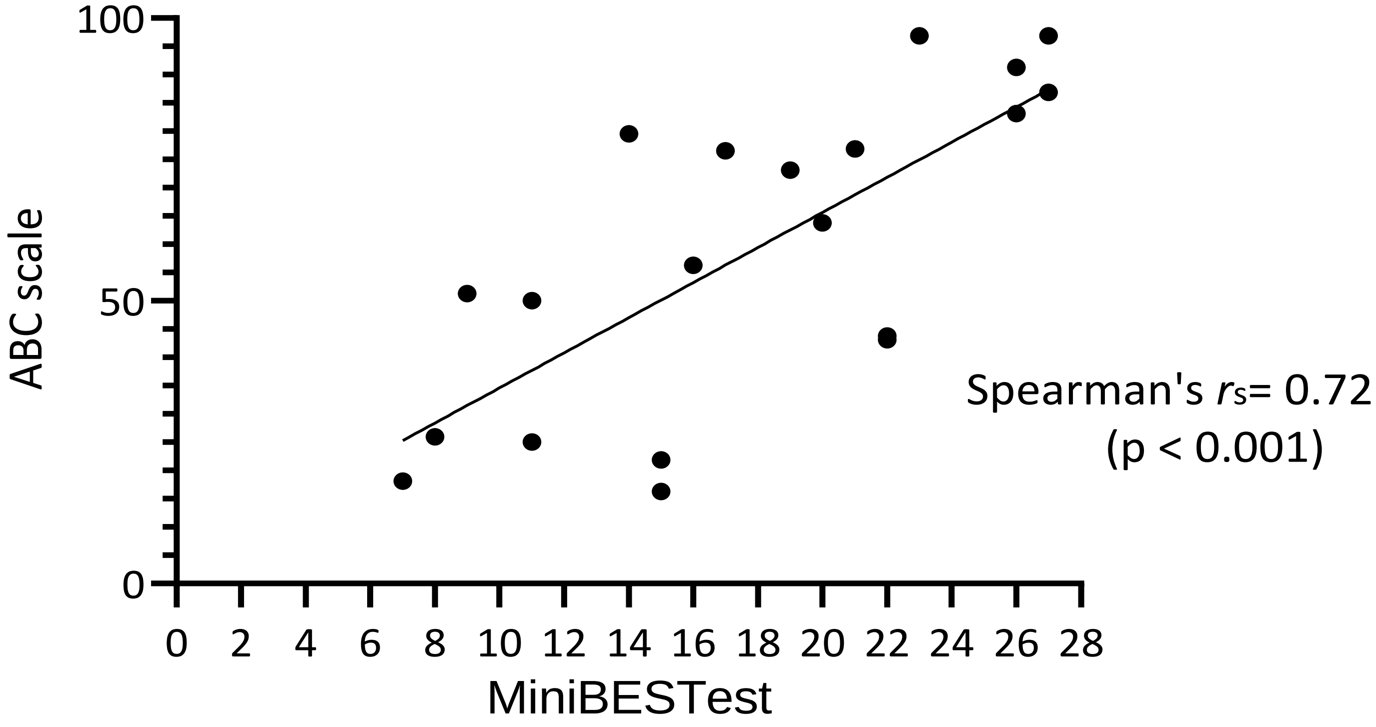


Figure 5—6 The association between the Mini-Balance Evaluation System Test (Mini-BESTest) and the Activities-specific Balance Confidence (ABC) Scale in the stroke survivors' group, Spearman's Correlation r_s =0.72 ($p < 0.001$).

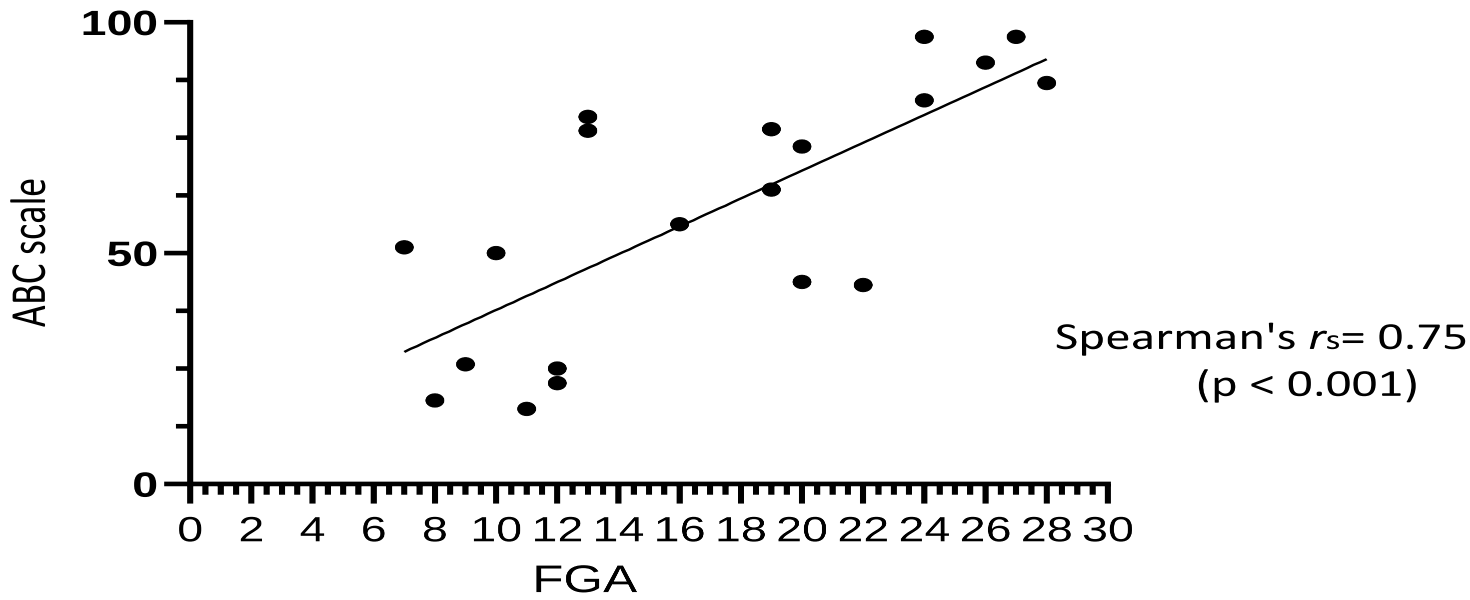


Figure 5—7 The association between the Functional Gait Assessment (FGA) and the Activities-specific Balance Confidence (ABC) scale, Spearman's Correlation rs = 0.75 (p<0.001).

5.3.5 Physical activity levels

Two participants from each group wore the accelerometer for less than 6 days and their data was therefore not included in the analysis. The flow chart illustrated in Figure 5-8 shows the AX3 accelerometery data included in the analysis.

The cut-off time for the level of PA in each individual is presented in Table 5-10. Percentage levels for PA every 10 minutes over 7 days were 85.7% sedentary (< 1.5 MET), 6.4% light (< 3 MET), 7.6% moderate (> 3 MET< 6 MET), 0.2% vigorous (> 6 MET) in stroke survivors (Figure 5-9); 87% sedentary, 5.9% light, 6.8% moderate, and 0.1% vigorous in healthy controls (Figure 5-10). No difference was noted between-group in PA levels.

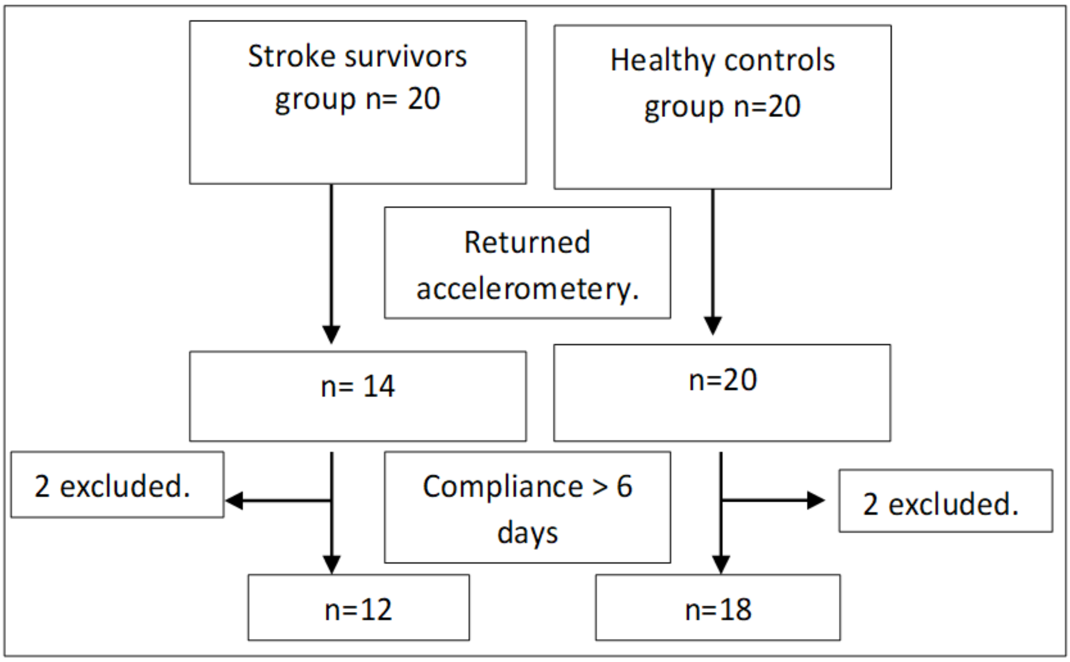


Figure 5-7 Flow chart of the AX3Accelerometery included for analysis.

			Stroke survivors (n=12)			Healthy control (n=18)		
Level of physical activity	Sedentary minutes (< 1.5 MET)	Light minutes (< 3 MET)	Moderate minutes (> 3 MET< 6 MET)	Vigorous minutes (> 6 MET)	Sedentary minutes (< 1.5 MET)	Light minutes (< 3 MET)	Moderate minutes (> 3 MET< 6 MET)	Vigorous minutes (> 6 MET)
Median	8.56	0.69	0.60	0.001	8.84	0.58	0.61	0.0005
Range	7-9	0.29-1	0.19-1.93	0-0.14	7.59-9.44	0.2-1	0.31-1.40	0-0.11
Percentiles								
25	8	0.39	0.31	0.00	8.38	0.42	0.42	0
75	9	0.85	1.07	0.01	9.03	0.68	0.79	0.003

Table 5-10 Cut-off point of Physical Activity (PA) from AX3 accelerometer for the stroke survivor participants and healthy control participants. Metabolic activity (MET) was used to determine the level of the PA - which is classified as sedentary, light, moderate or vigorous activity - over 10 minutes.

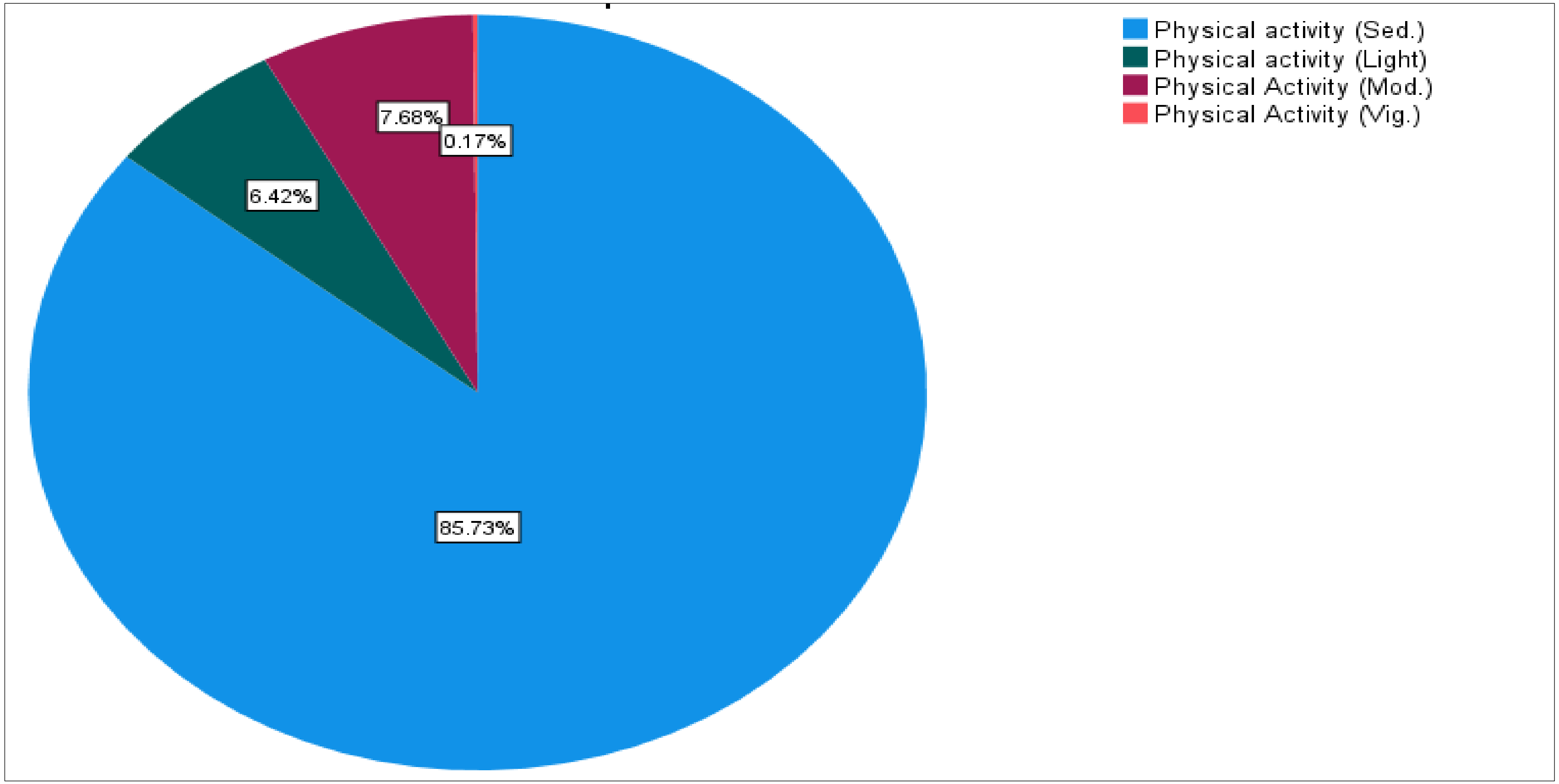


Figure 5-10 Pie chart for the percentage of Physical Activity (PA) levels in stroke survivors, Metabolic activity (MET) was used to determine the level of the PA which is classified as sedentary, light, moderate or vigorous activity - over 10 minutes.

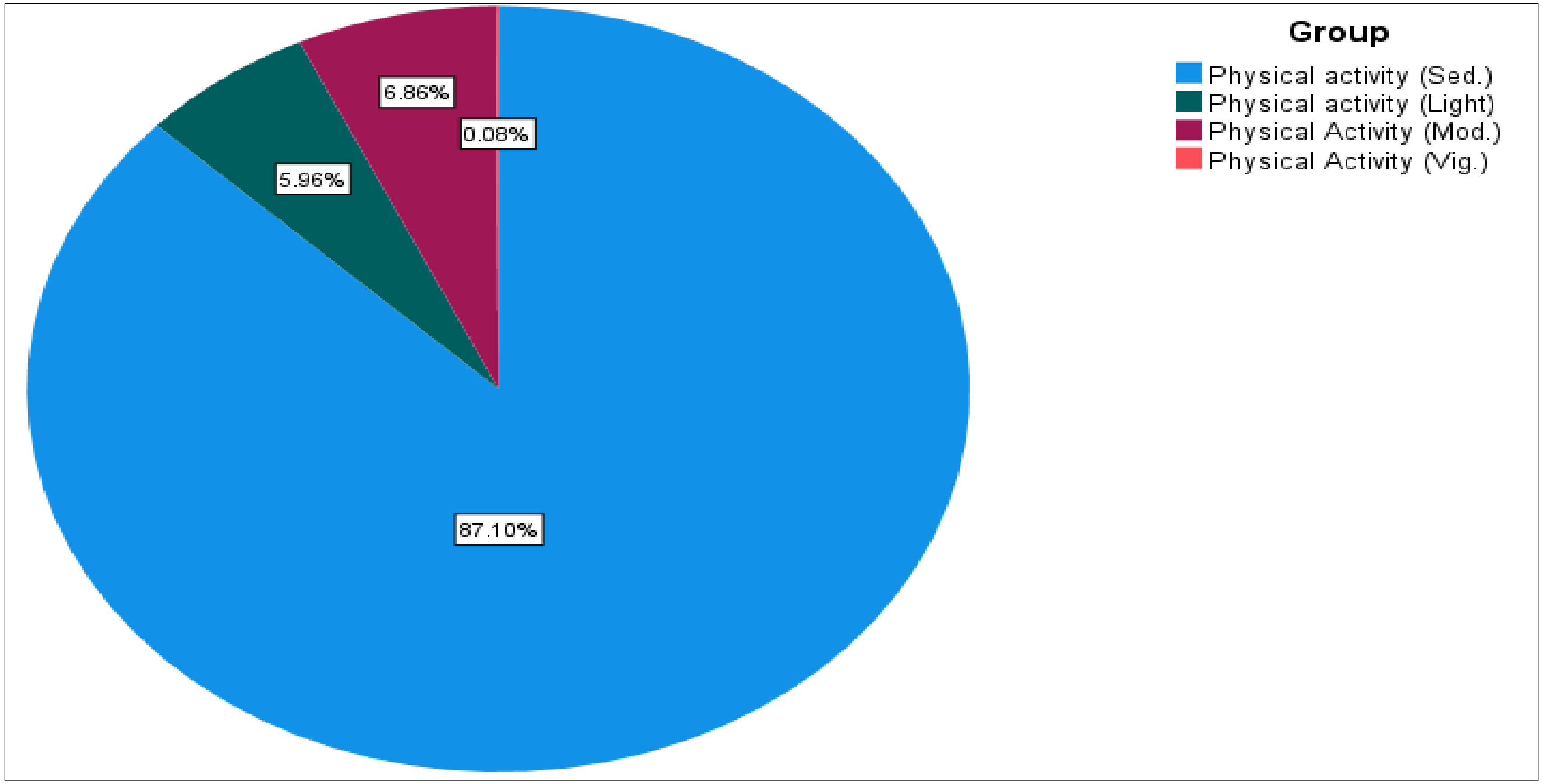


Figure 5-11 Pie chart for the percentage of Physical Activity (PA) levels in healthy controls, Metabolic activity (MET) was used to determine the level of the PA which is classified as sedentary, light, moderate or vigorous activity - over 10 minutes.

5.4 Discussion

The aims of this study were to identify factors associated with walking at a functional level in chronic stroke survivors compared to healthy controls. In the current study, walking at a functional level was assessed by the Mini-BESTest and FGA (294,421). The Mini-BESTest includes tasks to test anticipatory and reactive postural control, sensory orientation, such as standing on a foam or inclined surface, and dynamic gait tasks such as the Timed Up and Go (TUG) test and the TUG test with a dual concurrent cognitive task (counting backwards) (294). The FGA includes tests with complex tasks such as tandem walking and walking with head turns or stepping over an obstacle (421).

All stroke survivor participants in the current study were in the chronic stage, with duration from stroke onset ranging from one to 21 years. Participants were 70% females and 60% had left sided hemiparesis. Recruitment time was limited and in addition this study took place during the Covid-19 pandemic, with lockdowns also affecting recruitment. Therefore, it was not possible to optimise gender and stroke location among the cohort. In future studies, gender matching between groups with similar numbers for each sex should be included as well as participants with varying stroke location to provide more comprehensive data for the general stroke population.

In the current study, all stroke survivor participants were able to walk more than 6 metres independently with or without an assistive device. The scores for the motricity index indicated good lower limb functional motor recovery, and no dizziness/vertigo were reported. The motricity index includes tasks from sitting such as full range of knee extension against maximum manual resistance (502,504,597). The assessment of lower limb motor recovery can be enhanced by adding more challenging motor tasks (598), for example, the number of squats a patient can perform in 30 seconds (599). Furthermore, a more comprehensive assessment for motor recovery by Electromyography (EMG) (600) or a force plate (559) to assess the centre of pressure should be included in future studies.

The significant difference in the Mini-BESTest and the FGA between the ambulatory chronic stroke survivor group and healthy controls emphasises the need for rehabilitation to improve walking at a functional level for ambulatory stroke survivors. The mean score of the Mini-BEST in stroke survivors group was at borderline and indicated increased risk of falls. The cut-off score for the Mini-BESTest, which indicates a history of fall in stroke survivors, is equal to or less than 17.5/28 (294), and nine participants had scores below the cut-off score. The FGA cut-off score for increased risk of falls has not been identified for stroke survivors (297) but in community dwelling, older adults scoring equal to or less than 22/30 indicate increased risk of falls (512).The assessment of dynamic balance and functional walking is a requirement for optimal functional walking rehabilitation and will help in prescribing exercises targeted to all balance components.

Furthermore, assessing other factors such as balance confidence and cognitive functions are important to provide more personalised treatment approach. A personalised approach is a key to improving functional recovery in stroke rehabilitation (601,602). For example, intensive rehabilitation can be suggested for chronic stroke survivors to improve recovery, and studies have shown that an intensive rehabilitation (3–6 hours/day, 4–5 days/week, ≥2 weeks) in a community clinic setting is feasible (603,604). However, there are some challenges as a qualitative study by Yoshida et al (2021) demonstrated, for instance stroke survivors have difficulties in intrinsic motivation and this affects the frequency of self-training and activity in their daily lives (605). This suggests the importance of assessing psychological factors such as confidence and motivations to improve walking at a functional level in stroke survivors. Interactive treatment programmes such as through telerehabilitation can provide self-training and more motivation compared to traditional exercise programmes and this is needed for ambulatory stroke survivors (332,360,606).

In the current study, walking at a functional level was associated with balance confidence only in the stroke survivors group. Meanwhile, in the healthy controls, none of the variables were found to be associated with dynamic balance and functional walking. The above findings for dynamic balance and functional gait will be discussed in the following paragraphs.

5.4.1 Factors associated with walking at a functional level

Balance confidence was the only factor significantly associated with dynamic balance and functional gait in the stroke survivor group, whereby higher (i.e., better) balance confidence scores were associated with higher (i.e., better) Mini-BESTest and FGA scores. Balance confidence contributes to self-efficacy, defined as a person's belief in their ability to succeed in a particular situation (481) - which plays an important role in the effort applied to a task and stress experienced when presented with a challenge (481). People with decreased balance confidence and self-efficacy may modify their behaviour to avoid activities and situations that increase symptoms and/or risk of falls (481).

The association between dynamic balance, functional gait and balance confidence is in agreement with a study by Robinson et al (2011) which found that in stroke survivors (mean ±SD age and time since stroke were 65 ±8 years, 85 ±89 months, respectively), self-efficacy (assessed by the Falls Efficacy Scale) was the only personal factor that had high correlation with community walking; other personal factors which didn't correlate were age, sex, comorbidity, fatigue and depression (263). Similar study by Durcan et al (2016) for chronic stroke found that balance confidence (assessed by the Activities Specific Balance Confidence Scale) was the only factor associated with gait speed (10 metres walk and TUG tests); other factors which didn't correlate were fatigue, depression and anxiety (576).

Understanding the relationship between balance confidence and dynamic balance and functional gait and addressing this together with self-efficacy should be an important interventional target which may result in improved functional outcomes. Two studies of stroke survivors that targeted improving balance confidence through a balance awareness programme (607) and cognitive behavioural therapy (608), and in both studies increased balanced confidence helped in minimising fear of falling and improving balance function in stroke survivors.

All studies of stroke survivors to date have only used the Activities-specific Balance Confidence Scale (520) to assess balance confidence and self-efficacy (536,576,609). It is suggested that an interview is added to identify the level of confidence in performing certain activities, which might help in assessing balance confidence. Additionally, assessment of self-esteem such as the commonly used Self-esteem Stability Scale can be used (610). However, this scale is quite broad and needs to be modified to assess self-esteem for mobility after stroke. Recent evidence suggests that practising more complex activities within a rehabilitation programme improves balance confidence. (611). A pilot study of 21 chronic stroke survivors with reduced dynamic balance ability found that adding an intense and unpredictable perturbation during gait training led to an increase in the Activities-specific Balance Confidence scores (611), however, self-efficacy was not assessed.

Meanwhile, a review of older adults by Büla et al (2011) showed that multicomponent behavioural group interventions provided the most robust evidence of benefits in improving balance confidence and in decreasing activity avoidance (612). The 'Coventry, Aberdeen & London – Refined' (CALO-RE) Taxonomy of Behaviour Change Techniques was used in the study to identify physical activity behaviour (e.g., self-efficacy, attitudes, motivation, intentions, risk perceptions). The CALO-RE taxonomy can help in goal setting and behavioural changes such as increasing knowledge or understanding to induce positive feelings or stimulate action (613). A meta-analysis of 9 randomised controlled studies of stroke survivors, conducted by Stretton et al (2017), identified that incorporating at least one behaviour change technique (as defined by CALO-RE taxonomy) (613) to a treatment plan is better than exercises alone in improving real-world walking in stroke survivors (614).

Other variables tested for association with walking at a functional level (Mini-BESTest and FGA) in the present study were SVV, cognitive functions, depression, anxiety, walking in different environment (i.e., the Environmental Analysis Mobility Questionnaire – encounter and avoidance), quality of life related to health condition and quality of sleep. No associations were identified between any of these factors and either dynamic balance or functional gait. These factors are discussed in the following paragraphs.

5.4.2 Factors showing no association with walking at a functional level

5.4.2.1 Subjective Visual Verticality

All participants completed the Rod and Disc Test, except for one participant who complained of severe dizziness after focusing on the computer screen in the dynamic condition and did not complete the test. Although only one stroke participant complained of severe dizziness after the Rod and Disc test, it is suggested that a longer break is taken between each test to reduce dizziness.

The degrees of static and dynamic SVV were within normal ranges in both groups. Previous work has shown that visual dependency is more common in stroke survivors who have had a brainstem or cerebellar lesion (523), but 95% of participants in the current study had a cerebral hemispheric lesion, and only one participant had a cerebellar lesion. Similarly, vertigo as assessed by the Situational Vertigo Questionnaire was within a normal range for stroke survivor participants because vertigo is more common in posterior circulation stroke (95). Additionally, the lack of significant association could be due to the small sample size.

There was no association between SVV and dynamic balance (Mini-BESTest) or functional gait. All stroke survivors who participated in the current study were in the chronic phase (i.e., a minimum one-year post stroke), and it is possible that their SVV could have normalised since their stroke (569). Bonan et al (91) reported that sixty five percent of stroke survivors were more reliant on visual cues for balance control in the acute phase (91), but the association was not clear in chronic stroke survivors.

5.4.2.2 Cognitive functions

Previous studies on stroke survivors have shown that moderate or severe cognitive dysfunctions are associated with poor balance and limitations in functional ability (615). In addition, poor balance function has been found to be related to cognitive impairment and increased falls risk in stroke survivors (616). However, no associations were observed between Mini-BESTest or FGA and cognitive functions in the current study. Stroke participants in this study had average MoCA scores that were within a normal range or showed mild cognitive impairment in cognitive functions, which may be a factor contributing to the current findings.

It is possible that a larger sample size, including participants with varying cognitive functions post-stroke, could provide further insight into the associations between dynamic balance and functional gait with cognitive functions in this population. Findings from previous studies have shown an association between balance and cognitive functions in stroke survivors with moderate and severe cognitive impairment (209,616). This is most likely due to the difference in cognitive functions for participants in the current vs previous study and the small sample size in the current study.

The CANTAB tests were used to assess the cognitive functions in the current study, however, further studies are needed to assess cognitive motor interference and identify the ability to perform simultaneous cognitive tasks while walking (219,260,568). Since walking at a functional level requires carrying out concurrent simultaneous activities - DT walking, it is suggested future studies include DT walking tests and assess the association with cognitive functions.

5.4.2.3 Psychological aspects

Although previous studies show that walking in community was associated with environmental factors in stroke survivors (261,263,566), no associations between dynamic balance and functional walking and the environmental factors was noted in the current study, which could be related to the small sample size. Encounter and avoidance behaviour in relation to environmental factors was assessed by the Environmental Analysis of Mobility Questionnaire which determine frequency of encounter versus avoidance of environmental features affecting community walking (617). This questionnaire includes 21 features of the physical environment grouped into 8 dimensions: distance, temporal, terrain, ambience, physical load, postural transitions, attention, and density for instance crowded conditions (617). Encounter and avoidance behaviour should be assessed further, such as with an interview - to clarify, for example, number of trips, the level of participation, and ways to handle difficulties in walking in the community (250). In addition, the interview will help in clarifying the lifestyle behaviour before and after stroke (618). Other assessment strategies with wearable sensors, which could help provide additional and detailed information regarding walking on different terrain and managing speed changes while walking (619,620).

Moreover, different environments require different muscle activities, largely because muscle activation varies in relation to the environment, as has been observed in a cohort of stroke survivors (621). For example, community-based walking has been found to require increased muscle activity from the paretic lower limb compared to performing the same task in a controlled laboratory environment (621). Training in different environments may help increase a person's ability to mobilise in these environments (622).

A qualitative study of a cohort of stroke survivors by Twardzik et al (2022) showed that community walking is associated with environmental dimensions especially in more challenging environments such as walking on inclined surfaces or stair climbing, and can cause social stigma (623). Social stigma is defined as a negative attitude or idea about physical or social feature/s of a person or group of people that implies social disapproval and occurs when society or the general public shares negative thoughts or beliefs about a person or group of people (624). Wan et al (2023) developed a scale to evaluate public stigma for stroke survivors which include four factors: inherent ideology, aesthetic feelings, avoidance behaviour, and policy attitudes. (625). This scale could be used in future research and clinical practice to identify if stroke survivors have a public social stigma. Problems such as avoidance of walking in unfamiliar environments and social stigma in turn increase the limitations of walking in the community and can increase deconditioning in muscles (i.e., sarcopenia) and thus affect balance and functional ability.

In the present study, the scores for depression and anxiety were within normal ranges for all participants, except for one whose score showed borderline anxiety symptoms on the Hospital Anxiety and Depression Scale. Thus, no difference between stroke survivors and healthy controls were found in these scores, as with the quality of life related to health condition.

Furthermore, quality of sleep (i.e., the Pittsburgh Sleep Quality Index, and the Epworth Sleepiness Scale) was assessed, and no difference was noted between-group. However, a previous study by Moon et al (2018) showed a negative impact of sleep disturbance on balance in a cohort of sub-acute stroke survivors (230). Another study by Kim et al (2017) on 241 patients with acute ischemic stroke found that poor sleep quality was associated with poor general wellbeing (626). In addition, a study of 33 chronic stroke survivors by Martynowicz et al (2019) showed that excessive daytime sleepiness had a positive association with heart rate during sleep ($r = 0.46$, $p < 0.05$) and led to lower oxygen saturation ($r = -0.458$, $p < 0.05$) (627). There is a need for further studies to identify the association between dynamic balance or functional gait and quality of sleep and daytime sleepiness.

5.4.2.4 Physical Activity levels

The wrist- worn AX3 accelerometer was used to measure the level of PA in in all participants in both groups. Participant compliance for duration of wearing the accelerometer time was in line with previous studies showing that 7 days is convenient (531). However, in the current study only 12 stroke survivor participants completed the PA assessment, and the number of monitors returned by stroke survivors were less than anticipated. Three stroke survivors returned the monitors, but one of the monitors were damaged, which the participant said was due to exposure to oil. The other two monitors were worn for less than 6 days, and participants did not explain the reasons of not adhere to the duration in the follow-up. Three other monitors were lost since the monitor collection period was during the Royal Mail strike of 2022 (628). This might indicate that more procedures for follow up are required in future studies, including a daily follow up call and collection point.

Previous studies have shown that stroke survivors have lower PA levels than healthy adults (507,629), due to body impairment and functional loss (56). In the current study, all stroke survivor participants and healthy controls had high level of sedentary time throughout the day, which is in agreements with previous studies for PA (56,531). Additionally, the fact that the recruitment period may have affected the PA level when restrictions during the COVID-

19 pandemic were active during the data collection of the current study (630). In addition to COVID-19 restrictions, the seasons were a factor noted in a previous study which might affect the level of PA (531).

In addition, the level of PA in the current study was assessed by energy expenditure. A review by Kramer et al (2016) reported that stroke survivors consume more energy expenditure than healthy controls for the same activity (631). In this review, 29 studies (501 stroke survivors and 123 healthy controls) were assessed to determine energy expenditure using volume of oxygen uptake (VO2) (mL/kg/min) and energy cost in oxygen uptake per metre walked (VO2/walking speed; mL/kg/m) (631). It was found that energy expenditure during steady overground walking at matched speeds was significantly higher in stroke survivors than healthy controls (the mean difference in VO2, 4.06 mL/kg/min; 95% confidence interval, 2.21-5.91) (631).

Another study by Hobo et al (2021) recruited 36 stroke survivors (median stoke onset 47.5 days) to identify the correlation between the status of energy expenditure (kcal) in sub stroke groups according to physical function (632). The study showed a correlation between energy expenditure and the low score Berg Balance Scale group (median 47 out of 56 — a score of < 46 indicates greater probability of falling (632)); the Spearman's correlation was 0.69, p <0.01, but no correlation in the high score Berg Balance Scale group. The Hobo et al (2021) study showed that energy expenditure can vary depending on stroke survivor functional level, however, the sample size was small and further studies are required.

5.4.3 Limitations of the study

The current study was limited by a small sample size and time restrictions. Recruitment occurred mostly during the COVID-19 pandemic lockdowns which contributed to the difficulty in recruitment in both groups. Due to the small sample size and non-normally distributed data, the analyses were based on non-parametric tests according to ranking, which is less robust than parametric statistical analyses.

The results in the current study are limited to stroke survivors with a good level of functional motor recovery in the lower limb (motricity index > 43 out of 100 points). There is a need to include participants in different motor recovery stages and if possible, with larger sample to have a subgroup. Although the motricity index includes a functional lower limb motor assessment, there is a need for a more comprehensive assessment of motor recovery and joint stability especially for the ankle joints, due to the direct effect on balance and gait.

To assess walking at a functional level, the Mini-BESTest and the FGA were used, and both include tasks to test dynamic balance and complex gait, while the Mini-BESTest includes the TUG test with a mental subtraction task. However, there is a need to add more challenging assessments to test motor-cognitive tasks, such as including more cognitive tasks in the DT walking test.

Essential cognitive functions for walking safely include a) motor planning which is the ability to plan the sequence of movements required to walk, including initiating steps, adjusting stride length, and navigating obstacles; b) spatial awareness which is understanding the surrounding environment and one's position within it to avoid obstacles and make spatial judgments; c) attention, especially in complex environments in presence of distractions; d) executive functioning, which helps organise thoughts and actions, such as adapting to changes in speed or direction during walking; e) memory recalling familiar routes and remembering to avoid obstacles. All these cognitive functions are important and need to be assessed in DT walking in ambulatory chronic stroke survivors to walk safely and effectively in various environments (481,633).

Recruitment was based on the convenience snowball method which is respondent-driven, and has the advantage of reaching a wider population in a limited time (634). However, the sampling method can affect the sample (635); in this study the sampling ratio (i.e., male/female ratio, a ratio of the type of stroke, and the hemiparesis side (left/right/both) after stroke) was not matched, which negatively affected generalisability.

Additionally, there is a lack of homogeneity in the current study, stroke survivor participants had a chronic stroke more than 3 months previous, with a duration of stroke onset ranging from one year to 21 years. However, participants were 70% females and 60% had left sided hemiparesis. The time of recruitment was limited, and it was challenging to optimise gender and stroke location among cohort. In future studies, a more varied set of participants should be recruited to provide a more comprehensive results for general stroke population.

The MoCA was used as a screening tool (495) for cognitive impairment. Despite the feasibility of the MoCA test, the test can be difficult for stroke survivors with moderate to severe aphasia (636,637). Therefore, limits the generalisability of the study for stroke survivors with aphasia and moderate or severe cognitive impairments. There is a need to include more diverse participant for example, stroke survivors with aphasia and different cognitive dysfunction in further studies.

The assessment should also include upper limb strength, as a previous study by Rafsten et al (2019) showed that upper limb motor function (i.e., Fugl-Meyer Assessment-Upper Extremity scale) had an association with balance (i.e., BBS and TUG test) (638). Additionally, trunk control can be an early predictor of functional recovery after stroke (393,639,640). A recent study on older adults with sarcopenia showed that weakness of trunk muscle strength causes a decrease in walking velocity (641). Similar findings were reported in a group of older adult women (aged >65), that trunk muscle strength was associated with better activity performance (642). Further studies are needed to identify the association between upper limb motor function, trunk control, and walking at a functional level in ambulatory stroke survivors.

Other factors that may have an association with walking at a functional level include personal factors, for example, lifestyle, educational level, and demographics. Because of the difficulty in controlling personal factors, a short interview could be added before the assessment to help in screening personal and environmental factors. Additionally, there is a need to explore the impact of communication level, and if there are other current or previous co-morbidities, age, and respiratory health, such as chronic asthma, uncontrolled hypertension, and pain.

Furthermore, the AX3 accelerometer has several limitations. Studies have shown that the accelerometer provides more accurate data if it is placed on the lumber spine area (Lumber 5) or if 2 sensors are worn, one on each ankle, to provide more accurate gait parameters for step and stride timing asymmetry (643). However, multiple studies have shown that for a more convenient application over a 7-day duration, the accelerometer can be worn on the wrist (6).

5.4.4 Conclusion

In conclusion, this study confirms the decrease in walking at a functional level (dynamic balance and functional gait) in ambulatory chronic stroke survivors. The study found that balance confidence is the only factor associated with walking at a functional level in stroke survivors. These preliminary findings need to be confirmed in larger studies. It is conceivable that inclusion of a balance confidence assessment may lead to a more multifactorial, holistic treatment approach which may result in better outcomes. It may be that a targeted, multifactorial treatment approach which also addresses factors associated with balance and gait, may result in improved stroke rehabilitation outcomes. Further research is required to understand the association between walking at a functional level and the perception of SVV, mild cognitive dysfunction, depression, anxiety, quality of sleep and physical activity level.

Chapter 6: Feasibility of the HOLOBalance System for Balance Training for Older Adults at Risk of Falls

6.1 Introduction

Falls are a common and costly public health issue in older adults. One in three people aged 65 and over fall annually (47). In view of a rapidly ageing population, the economic burden of falls in older adults is increasing (644). Falls in older adults are associated with sedentary behaviour, social exclusion, and can result in serious injuries (82,117,645–649). Causes of falls are multifactorial; the main cause is balance dysfunction (82,645,646). The main factor behind balance dysfunction is related to impairments in the vestibular system (48,117,378,650–653); about 80% of older people who fall were suffering from vestibular impairment (48). Furthermore, an age-related decline in all sensory inputs and functions is well recognized and leads to balance dysfunction (117,647).

On the other hand, the decline in cognitive processing, mainly in terms of executive function and attention, is common in ageing and is associated with balance problems, reduced dual-tasking ability, reduced walking speed and an increased fall risk (654). Cognitive impairment is strongly associated with impairments in activities of daily living and functional independence (655), impaired balance and increased risk of falls (656).

To reduce the risk of falls in older adults, there is a need to improve balance function, traditional rehabilitation is patients follow sets of physical exercises prescribed by a healthcare professional (327,329). Although exercises are brief and easy to perform, there is up to 50% loss in follow-up rate in the home exercise programmes in older adults (73). While supervision significantly increases compliance and effectiveness, it is costly to provide (657).

Therefore, many fall rehabilitation programmes for older adults rely upon patients performing exercises independently at home (658–662). These programmes typically provide simple balance and strengthening exercises (e.g., leg strengthening, simple walking) for individuals to complete at home. Although these programmes have been shown to be effective in reducing falls rates by approximately 30% in older adults, the exercises do not include training for vestibular and cognitive function (659–661), or might be prescribed very late in the programme (662,663).

Therefore, it is essential that all components of the balance system (i.e., vision, vestibular system, proprioception) are added to the exercise rehabilitation. Previous studies have shown that Multi-sensory Rehabilitation (MSR) exercises reduce vestibular dysfunction, and exercises using adaptation, eye head coordination, postural responses, gait and function retraining (80,327,328), are more beneficial than traditional interventions (329,383). Multifactorial aspects of balance assessment and treatment need to be addressed as recommended by NICE guidelines for older adults at risk of falls (664). Previous studies have indicated that when exergames (i.e., interactive gamification) are combined with physical exercises, results showed enhanced cognitive function, social wellbeing, and quality of life (665–667).

Technology-based solutions such as telerehabilitation, which use a range of new technologies including virtual and augmented reality (VR, AR), gamification, sensor based monitoring and real time patient feedback, can support the provision of multifaceted falls rehabilitation (69,344,668). Multiple studies have indicated that the use of telerehabilitation motivates patients and promotes exercise adherence towards long-term behaviour changes in older adults (342,669,670). For example, a newly developed telerehabilitation - the COCARE -

system to improve motor functioning - was found to be feasible for older adults (354,355). Similarly, the STASISM system (357), has not been tested for older adults. In both systems the exercises were limited and lacked progression and personalisation. A telerehabilitation system should provide a variety of more personal exercises according to personal needs which allow progression through the treatment period for better improvement in balance control. There is a need for 'designed for purpose' interactive technologies which can both allow and guide clinician- prescribed MSR exercises for older adults at risk of falls. Most previous studies that used commercial exergames for fallers did not allow for customised MSR based on clinical assessment or collect physiological, movement, and cognitive outcome data. In addition, existing platforms for fallers do not address all the key facets of MSR exercises.

The HOLOBalance telerehabilitation system was designed to provide MSR exercises that addresses the needs of older fallers (376,377). It presents the MSR exercises, exergames and cognitive training in an augmented reality (AR) training programme. The use of exergames such as memory games in an AR environment can help in enhancing cognitive function and providing increased motivation to patients. The HOLOBalance system also enables exercise performance monitoring and user interaction by means of body-worn sensors, provision of individually prescribed exercises and exergames (376,377).

The aim of this study is to investigate the feasibility and acceptability of using the HOLOBalance system for balance training in older people at risk of falls. The feasibility of HOLOBalance for older adults at risk of falls was run at the same time in other research centres in Athens, and Freiburg. Multicentre study increases the number of participants from different geographic locations which helps in including a wider range of population groups (671,672).

6.1.1 Study objectives

Primary objectives: are to investigate the feasibility and acceptability of implementing the supervised HOLOBalance/ HOLOBox intervention for balance training for older adults at risk of falls.

Secondary objectives: To explore trends for effectiveness in physical, cognitive, and psychosocial aspects in the intervention group compared to usual care balance rehabilitation for older adults at risk of falls. Specific secondary objectives were:

i. To determine whether there are improvements in balance (Mini-Balance Evaluation Test (Mini-BESTest) and gait function (Functional Gait Assessment (FGA)) in the intervention group compared to usual care balance rehabilitation.

ii. To determine whether there are improvements in cognitive function (Cambridge Neuropsychological Test Automated Battery (CANTAB) tests) in the intervention group compared to usual care balance rehabilitation.

iii. To determine whether there are improvements in subjective symptoms such as fears of falls (the Falls Efficacy Scale International) and balance confidence (the Activities-specific Balance Confidence Scale) and other subjective symptoms in the intervention group compared to usual care balance rehabilitation.

6.1.2 Hypotheses

Primary hypothesis: The HOLOBalance/ HOLOBox system will be feasible and acceptable for balance training for older adults at risk of falls as determined by semi-structured interviews and usability scales.

Secondary hypothesis: There will be greater improvements in balance and gait function measurements (Mini-BESTest and FGA) respectively, cognitive function tests (CANTAB tests) in addition to subjective symptoms tests in participants enrolled in the HOLOBalance/ HOLOBox intervention group than in the control group.

6.2 Methods

6.2.1 Study design

This was an assessor-blinded, randomised controlled feasibility study, which adhered to the Consolidated Standards of Reporting Trials (CONSORT) (673). A clinic-based (HOLOBox group) and home-based (HOLOBalance group) MSR exercise programme, delivered via the HOLOBalance System were compared to standard care delivered using the Otago Exercise Programme (674). Ethical approval was granted by each study site's Human Research Ethics Committees in the UK (19/LO/1908), Germany (265/19) and Greece (9769/24-6-2019). All participants provided written informed consent.

6.2.2 Study settings and recruitment

Participants were recruited from aged care organisations and community support groups. The study setting for the HOLOBOX group, and the control was at the research laboratories of the Centre for Human and Applied Physiological Sciences, Guy's campus, at KCL in London (UK), and in a laboratory setting in clinics in Freiburg (Germany), and Athens (Greece).

Participants in HOLOBalance group had the treatment sessions at their homes, and they had the treatment session every day from the HOLOBalance system in each week from the therapist at the HOLOBalance platform (https://holobalance.eu/)

(https://portals.rrdweb.nl/holobalance/index.php). Participants received three home visits: the initial visit in week 1 to set up the equipment, a follow up in week 4, and the final session in week 8. Also, participants were able to ask through emails and telephone at any time.

6.2.3 Eligibility criteria

Independently living, community-dwelling older adults aged 65 to 80 years at risk of falls, defined as a Functional Gait Assessment (FGA) score <22 (296), Falls Efficacy Scale short form score >10 (551); and/or reported at least one fall in the previous 12 months were recruited. Additional inclusion criteria were able to perform > 500 m continuous mobility independent or with one stick assistance; able to understand and provide consent to participate; MoCA score >23/30 indicating no or mild cognitive impairment (495).

Exclusion criteria included orthostatic hypotension defined as >22 mm Hg fall in systolic blood pressure or >10 mm Hg fall in diastolic blood pressure within three minutes of standing up, as measured by sphygmomanometer; uncontrolled hypertension; significant visual impairment; Geriatric Depression Scale score >10/15 (517); neurological conditions; musculoskeletal lower limb injuries; parkinsonism; neuropathy; fractures; or spinal pain; participation in a clinical drug trial within the previous six months; receiving falls, balance, or cognitive rehabilitation at time of study; implanted medical devices or cardiac pacemaker in situ; ≥3 migraines per month.

6.2.4 Randomisation and allocation concealment

An online platform (www.sealedenvelope.com) was used to randomise participants on a 1:1:1 ratio into either an in-home (HH) or in-clinic (HB) delivered MSR exercise intervention, or a control group (CG) who completed the Otago Exercise Programme. Randomisation and intervention group assignments were conducted by researchers external to the study at each site. Assessors were blinded to intervention allocation. Allocation was concealed in consecutively numbered opaque envelopes and was presented to the treating physiotherapist and participants after baseline assessment completion.

6.2.5 Interventions

Each group received 8-weeks of rehabilitation, and all participants were asked to practise their prescribed balance activities for 45-minutes daily.

6.2.5.1 The active intervention: HOLOBalance (HOLOBalance HH or HOLOBox HB) balance rehabilitation programme

6.2.5.1.1 Description of the HOLOBalance and HOLOBox devices

HOLOBalance is an augmented reality balance training programme based on evidence-based MSR exercises (327,328). Balance exercise with MSR requires individuals to perform exercises which challenge the balance system and optimise vestibular balance function, for example closed eyes while standing on a foam. More details about the MSR are described below under the (Multisensory Rehabilitation MSR exercises) section. The clinical physiotherapist determined the exercises for each treatment session in the HOLOBalance platform. The HOLOBalance system used sensors that were worn on intact skin as depicted in Figure 6-1 below. Specifically:

- The Moticon Science insoles (Moticon ReGo AG, Munich, Germany) were inserted into a pair of shoes. Participants are always required to wear socks while wearing the provided insoles. The Moticon insoles are required to assess movements
- performed while completing the telerehabilitation programme for example step length which is calculated by dividing the total distance covered by the total number of steps which is specified as the number of heels strikes during gait (Step length = Distance/ Steps number) (675).
- Mbientlab MMR 9 axis Inertial Measurement Unit (IMU) (Mbientlab, San Francisco, USA) comprising accelerometer, magnetometer, and gyroscope. The Mbientlab MMR was used to record the position of body segments (head, trunk) and provided information on postural sway (from Lumbar IMU) when performing the HOLOBalance exercises. The Mbientlab MMU has been used in previous studies to assess gait (676), and IMU systems have been shown to be valid for the assessment of gait in numerous patient populations (677). The Lumbar IMU was attached using an elasticated Velcro strap around the waist at the level equivalent to the region L4-L5 of the lumbar spine. The Velcro strap was tightened around the waist and worn over clothes. The IMU recorded the location and movement of body segments when completing the telerehabilitation programme (e.g., trunk flexion).
- POLAR H10 Heart rate monitor (POLAR Electro Oy, Finland). The POLAR heart rate monitor was used to record heart rate intervals of participants while undertaking the HOLOBalance programme. POLAR heart rate monitors have been demonstrated to provide valid heart rate interval data when compared to ECG and have been used in numerous studies assessing heart rate and heart rate variability in the home

environment (678). The POLAR H10 heart rate monitor was worn around the thorax beneath the region of the heart and next to the participant's skin.

- The head mounted display (Mobile Phone Google Pixel 3XL, Docooler AR Headset for Smart Phones,) with attached IMU (Mbientlab MMR) was used to display the hologram to users and used to track the motion of the head and was securely fitted to the head via elasticated straps.

Participants were required to wear the body sensors (pressure detecting insoles, inertial measurement unit (IMU) and a heart rate monitor) when performing the exercises to enable the computer software to assess the participants performance and can provide instructions accordingly for example for safety to stop the exercise or to modify the movement if was not performed correctly.

Other Components of the HOLOBalance devices are described in Table 6-1 below. A pictorial guide is attached in Appendix 28.

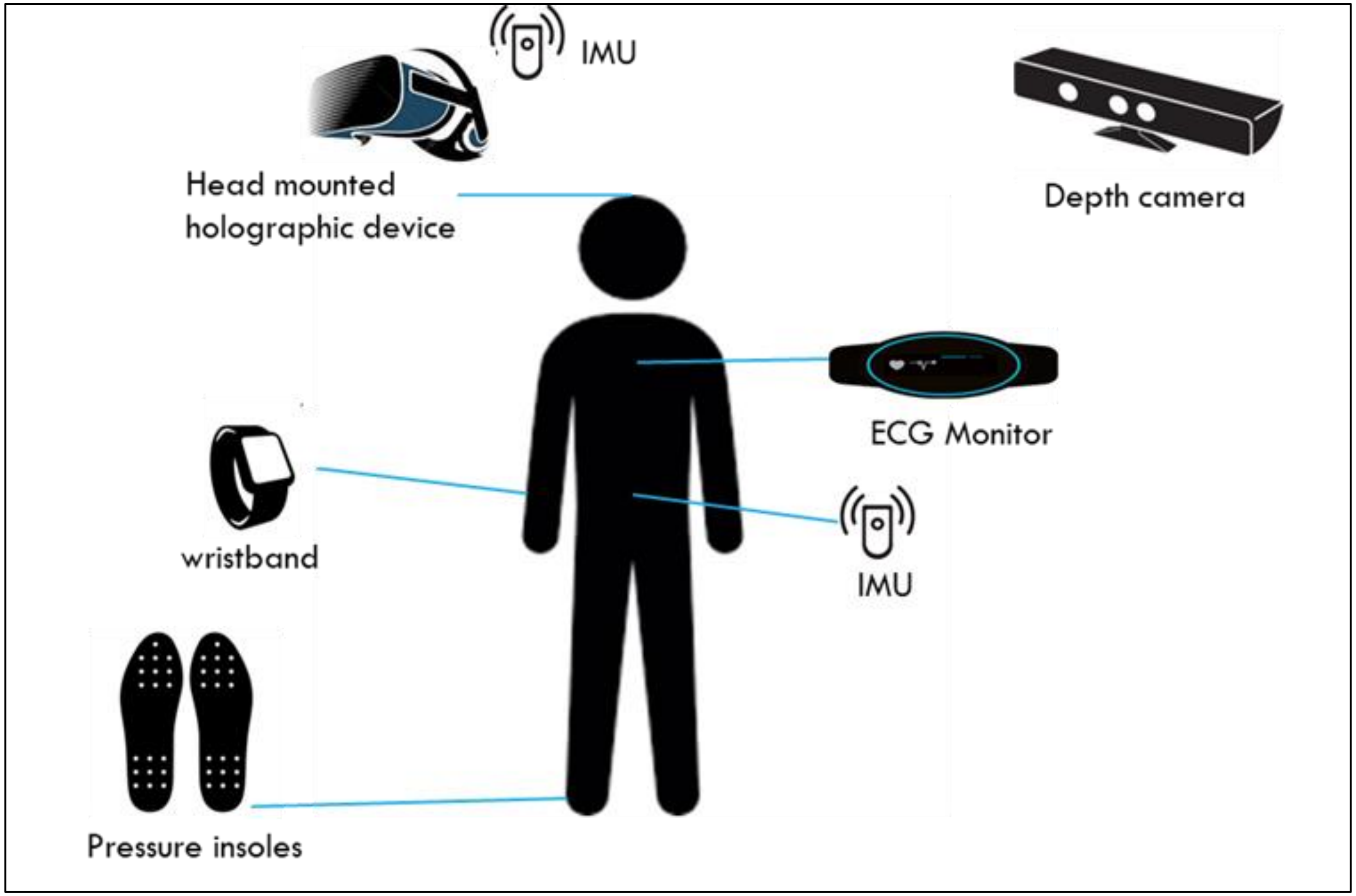
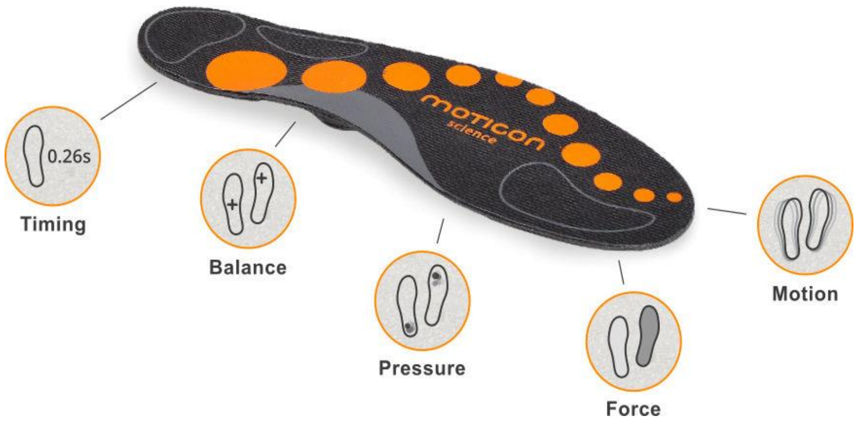


Figure 6—1 Positioning of HOLOBalance sensors.

Device	Model	Brief description
Edge Computer	Dell Inspiron https://www.dell.com/en-us/shop/dell-desktop-computers/inspiron-desktop/spd/inspiron-3670-desktop/fdcwgmmtcfl201s 	Windows 11 Intel HD Graphics 730
IMUs	MBientLab MMR https://mbientlab.com/metamotionr/ 	A clinical grade sensing solution is a wrist worn device that provides recorded (logging) or real-time (streaming) sensor data: - BMI160 / BMI270 3-axis Accelerometer - BMI160 / BMI270 3-axis Gyroscope - BMM150 3-axis Magnetometer - BOSCH 9-axis IMU Sensor Fusion - BMP280 Temperature | MMS ONLY - BMP280 Barometer/Pressure/Altimeter | MMS ONLY - LTR-329ALS Luminosity/Ambient Light | MMS ONLY
Depth Camera	Intel RealSense D415 https://gr.mouser.com/ProductDetail/Intel/82635ASRCDVKHV?qs=sGAEpiMZZMve4%2fbfQkoj%252bHmpIJ4wQb9YPb2aKdrbLy4%3d	It has a standard field of view well suited for high accuracy applications such as a 3D scanning. With a rolling shutter on the depth sensor. It offers the highest depth quality per degree.

		
Sensor Insoles	Moticon insole https://www.moticon.de/science/ 	Moticon insole combines accurate pressure distribution and force readings with cutting edge inertial motion sensors.
Heart rate monitor	Polar H10 https://www.polar.com/en/products/accessories/H10_heart_rate_sensor 	It is a monitor for heart rate with maximum precision and connects the heart rate to a great variety of training devices with Bluetooth.

Headphones	Sennheiser HD 200 PRO https://en-uk.sennheiser.com/studio-headphones-noise-reducing-hd-200-pro 	It is a closed-back around ear lightweight professional studio monitoring headphone 32 Ohms, includes 6.3mm stereo jack adapter and 2m cable.
Head-mounted Device		It is a display device, worn on the head or as part of a helmet that has a small display optic in front of one (monocular HMD). HMDs have many uses including gaming and aviation

Table 6-1 The components of the HOLOBalance devices

6.2.5.1.2 *HOLOBox setup*

The HOLOBox was used for the HOLOBalance at the clinic/lab setting for the presentation of a virtual therapist and exercise for the HB group. The HOLOBox is a 2-metre X 2-metre X 2-metre open cube made of metal pipes. A screen is stretched across the diagonal of the frame, and a rear projector projects the image onto the screen (Figure 6-2). The orientation of the screen and projector provide an image that appears to be 'floating' and three-dimensional within the HOLOBox. The patient is positioned in front of the HOLOBox to see the projected image and follow the instructions provided by the virtual physiotherapist.

Figure 6—2 The HOLOBox used for projecting the virtual therapist.

6.2.5.1.3 The Multi-Sensory Rehabilitation (MSR) exercises

The HOLOBalance/HOLOBox intervention is based upon established, evidence-based multi-sensory rehabilitation (MSR) exercise (328). The MSR requires individuals to perform exercises that challenge the balance system (e.g., closed eyes while standing on foam), optimise vestibular function (e.g., look at target and turn head left and right repeatedly) and have been shown to improve balance control in healthy older adults (328). These interventions have been widely used in patients with vestibular disorder (679–682), which was safe and showed significant improvements in balance (381,683–687). The MSR exercises are effective for older adults with vestibular problems (58) and can also help in decreasing dizziness (95).

Studies have shown that MSR exercises are feasible to provide for older adults who experienced falls (688–692) and improves balance function in older people who had a history of wrist fracture (691). Also, multiple evidence suggests that the MSR exercises are effective to improve balance for older adults (58,329,688–692,381,662,663,683–687). Therefore, the MSR exercises were implemented in the HOLOBalance/HOLOBox system. The exercises include training from sitting, standing, and walking to maximise opportunities for balance improvement, for example, standing on foam, turning head whilst looking at a target, and walking whilst turning head left and right, exercises are outlined in Table 6-2, also detailed in Appendix 29.

Progression in exercise was assessed every week after assessing the performance for prescribed exercises and asking participants to rate the difficulty and dizziness in analogue scale from 0 to 10. Participants were progressed in the exercise programme if their performance on specific exercise was achieved correctly with minimum difficulty and dizziness.

6.2.5.1.4 The home exercise programme

Participants in the HB have been asked to complete a personalised home exercise programme on the days they do not attend the treatment exercise session. The home exercises were incorporating MSR exercises under the provided safety guideline and precautions. The MSR exercises which were performed in the treatment session were followed for the home exercise, for example, if a participant did the exercises from sitting, the same exercises were provided for home programme. After progression in the MSR exercises from standing and walking in the treatment session, the same exercises were followed for home exercise. If a participant is at high risk of fall and needs supervision while performing some exercises such as walking while tuning head in a shape of V, the exercise was not prescribed for home exercise. The Home Exercise Log, attached in Appendix 30, was provided to record the exercises.

In addition to the MSR exercises, the HH and HB groups include the auditory tasks, exergames, and cognitive training, all are detailed below. The first auditory task was provided from week 1 and progress to the second auditor task from week 4. The exergames and cognitive training have been prescribed according to participant capacity and the clinical judgement, provided from week 4 and progress in exercises overtime depending upon the participant's task performance.

Position	Description	Progressions
Seated	Head turns side to side (yaw rotation of 30°) whilst visually fixating on a static target placed at eye level in front of the participant.	- Increase speed of movements - Visual target moves in opposite direction to head movement
Seated	Head turns up and down (pitch rotation of 30°) whilst visually fixating on a static target placed at eye level in front of the participant.	- Increase speed of movements - Look up to ceiling and down to floor without fixation
Seated	Bend down to pick object up from the floor in front of you	- Close the eyes - Reach to pick up objects to the side
Standing	Stand with feet hip width apart, looking straight ahead with eyes open	- Bring feet closer together - Close the eyes
Standing	Stand on foam cushion with feet hip width apart and looking straight ahead with eyes open.	- Bring feet closer together - Close the eyes
Standing	Stand with feet hip width apart and bend over to pick up an object from the floor	- Bring feet closer together - Reach up as if to reach into a cupboard
Standing	Turn through 180° to face the opposite direction.	- Increase speed of movement
Walking	Walk forwards looking straight ahead	-Increase walking speed
Walking	Walk forwards across the room looking between two targets placed at eye level, 1.5 metres apart on the horizontal plane.	- Increase walking speed - Increase head turn speed - Increase head turn amplitude when visual targets are removed
Walking	Walk across the room and nod your head to look up to the ceiling and down to the ground.	- Increase walking speed - Integrate diagonal head movements

Table 6-2 Multi-Sensory Rehabilitation (MSR) Exercises implemented to HOLOBalance programme.

6.2.5.1.5 Presentation of MSR exercises in the HOLOBalance programme

The MSR exercises were presented via a virtual physiotherapist, Figure 6-3, which was projected as a hologram, describes, and demonstrates the desired exercise, then asks the participant to perform each exercise. If a participant performed the exercise incorrectly the virtual physiotherapist asked him/her to stop the exercise and demonstrated the exercise again. The presentation of holograms helps to stimulate the visual cues, increase the user's motivation, and add more encouragement to do the exercises after having been demonstrated by the hologram.

The participants movements were recorded using the motion capture camera and the body worn sensors and were processed in real time by the edge computer so that the computer software can assess the participant's exercise performance.

Figure 6—3 A representative image of the virtual Physiotherapist taken as a screen capture from the HOLOBalance.

6.2.5.1.6 Exergames for balance training

Exergames are the presentation of gamification with the MSR exercise. All exergames are divided into three groups from sitting, standing, and walking. The introductory instructions include oral and written information about the gameplay and how to achieve the goal of the exergames. An example of exergames includes walking while focusing on a bird and adding head movement to follow the bird (to achieve head turning while walking) (Figure 6-4).

Figure 6—4 An example of an exergame from the HOLOBalance system.

6.2.5.1.7 Cognitive training

Cognitive training exercises were specifically developed to address specific cognitive function including reaction time, visuospatial working memory, pattern recognition memory and rapid visual information processing. The cognitive tasks are included in Table 6-3. Responses are provided by turning the head to highlight the response required, or by moving an item into position using head movements. Screen captures from live gameplay in augmented reality are shown in Figure 6-5.

Game	Description	Progression
Bridge crossing	There are multiple houses for animals. Each house is for 1 animal type. Your goal is to join the bridges to the correct path so that the animals can cross. You will have only a few bridges so you will need to move them often so that every animal can safely cross	Increase number of animals crossing
Path to shelter	Different animals are entering the scene and going to their house. They follow different paths, after the animal has arrived at their house you need to choose the path on which they went.	Increase number of animals crossing
Remember previous animal	Animals appear and disappear one by one. You need to tell if the previous animal was the same as the current one.	Reduce stimulus presentation time
Remember order	You will be presented with multiple cards with different animals. After some time, the cards will disappear and will appear again in other order. You will need to select the cards by the order that they appeared first.	More cards presented
Animal feeding	Animals of the same type are moving in front of you. Your goal is to feed the animal by selecting it. You are allowed to feed the animal only once.	Increase the number of animals
Preparing animal food	There are several different animals that will come to you to be fed. You will feed the animals by placing the correct food in any pot. Animals will approach and after they eat the food they will leave, and a new animal will wait in line to eat.	Increase the number of different animals and subsequent types of food to be given.
Catch food	There is a tree in front of you from which the fruit is falling. You need to catch the fruits with the basket.	Increase falling speed and range over which items fall.
Find unique fish	There are multiple fishes that are swimming in the aquarium. Only 1 is unique and you need to select that one.	Increase the number of fish in the tank

Table 6-3 Cognitive training programme to be implemented to HOLOBalance programme.

Figure 6—5 Real life view of the cognitive games "catch the Food" (top), and "remember previous animals (bottom) presented in augmented reality.

6.2.5.1.8 Auditory training

For the auditory training tasks, participants were provided with two separate tasks. In the first task, participants were asked to respond to a series of requests in the format, “Show the [animal] where the [colour] [number] is” (e.g., show the blue cat where the yellow 7 is). In the second task, participants were required to listen to excerpts from a story (Billy Elliot) and answer questions about the story. In both tasks, the difficulty was increased by raising the loudness of crowd babble played in the background.

6.2.5.2 The control intervention: Otago exercise programme

The control group received the Otago exercise programme (674,693) which is a systematic, progressive strength and balance training programme and is supported by a comprehensive workbook that provides written and pictorial instructions for each exercise (693). The Otago exercises are well-established and are widely used in clinical practice in the UK for the management of older adults who fall or have increased risk for falling. It has been shown to reduce falls rate in older adults by 35%, with the greatest effects observed in frailer older women (659–661,693). The Otago exercise has also been used as the standard intervention in a previous investigation in addition to MSR interventions in older adults at risk for falls (329).

The Otago exercise programme consists of circulatory warming up exercises, muscle strengthening exercise for lower limbs and exercises for balance such as walking in a figure of 8. Specific exercises from the Otago booklet were determined weekly according to participant physical level assessment for home exercise.

The recommendations from Otago guidelines were followed for the exercise parameters (i.e., frequency and intensity). Participants were asked to do the Otago exercise once daily, for strengthening exercises, each exercise should be graduated from tolerated ankle cuff weight (e.g. 2 kg) and gradually increased according to participants capacity. Balance training exercises were graduated according to the level of difficulties from supported to unsupported exercises such as walking on toes for 2-3 metres while holding a supporting surface and increasing the difficulty to walk on toes without holding (674,693).

Participants were required to log their exercises in an exercise diary for weekly review and progression in the supervised treatment session. Exercises were progressed in line with the recommendations of the Otago exercise in combination. The Otago exercise booklet has been provided to all participants in the control group. An example of exercises from the Otago booklet are attached in Appendix 31.

6.2.6 Screening

All participants have undergone a brief telephone screening for history of falls, depression status with the assessor prior to being enrolled into the study, and proceeded to the participant information sheet and signed the informed consent.

6.2.7 Outcome assessment

Participants in all groups were required to attend for the initial assessment (week 0) and final assessment (week 10).

6.2.7.1 Primary outcomes

The primary outcomes include compliance and adherence with the intervention, rates of withdrawal from the intervention, and acceptability of the intervention to participants. Adherence and compliance rates were assessed from the training log and schema data available for each participant in the HOLOBalance system software.

Feasibility and acceptability were assessed by the semi-structural exit interviews and questionnaires. More discussion was presented in Chapter 4 under section “4.5.1 Qualitative methodology approach for exit interviews” and section “4.5.2 Assessment of feasibility, acceptability, and usability of HOLOBalnce system”.

6.2.7.2 Secondary Outcomes

The secondary outcome measures are in the core area of Life Impact and the Domains of physical functioning, social functioning, emotional functioning, and cognitive functioning according to the Comet Initiative taxonomy of outcomes. These measures were collected by a blinded outcome assessor at baseline (week 0) and after completion of the 8-week exercise programme (week 9).

A. Physical balance and gait assessment included the following outcome measures:

- The Mini-BESTest (292)
- The Functional Gait Assessment (FGA) (512)
- Falls diaries were provided for participants to record whether they have fallen each day and needed to return falls diaries each week and after the intervention

had been completed, they returned the diary in postage paid envelopes each month for 3 months.

B. Cognitive assessment

- The validated MoCA (495).
- The validated Cambridge Neuropsychological Test Automated Battery (694); (CANTAB) cognitive test battery (513).

C. Self-rated questionnaires for the PA and social participation assessment

- The Rapid Assessment of Physical Activity (552).
- The World Health Organisation Disability Assessment Schedule 2.0 (550).
- The Falls Efficacy Scale International (551).
- The Behavioural Regulation in Exercise Questionnaire (553,554).
- The Activities-specific Balance Confidence Scale (695).

More explanation about the tests and self-rated questionnaires were included in Chapter 4 (General Methodology) under section "4.3 Assessment of physical, cognitive function and activity limitation".

6.2.8 Discontinuation/ withdrawal of participants from study treatment

Each participant had the right to withdraw study at any time. In addition, the investigator had to discontinue a participant if a participant missed 15 consecutive days of exercises; or had an acute/severe illness that severely impacts upon their ability to continue in daily exercise; or had an acute orthopaedic injury; or acute neurological impairment or loss of vision; or was lost to follow up. If a participant withdrew from the study due to non-compliance a request for feedback was made asking what they perceived led to their lower-than-expected levels of compliance with the intervention. Participant/s who withdrew due to an adverse event, were followed-up until the adverse event has resolved or stabilised.

6.2.9 Statistical analysis

The primary objectives were to determine the feasibility and acceptability of the HOLOBalance / HOLOBox plan, with data being collected to determine dropout rates and compliance. A pragmatic sample size of 10 per intervention arm has been deemed appropriate for a feasibility study (594). As this was a short duration feasibility study there was no formal plan for statistical analysis due to the small sample size and lack of statistical power. The scores representing the higher frequency (mode) of User Experience Evaluation questionnaires were determined. Participants exit-interviews were analysed using the 6-stage thematic approach described by Braun and Clarke (546).

Data normalities were checked with skewness, and kurtosis for the secondary outcomes (physical, cognitive tests and self-rated subjective assessment); since the data were not normally distributed, non-parametric statistics were used. Descriptive statistics were used and nonparametric Kruskal Wallis test was used to provide insight for the difference and see the trends in improvement between the HOLOBalance, HOLOBox and the control groups. Post hoc analysis with Mann-Whitney U tests were performed to identify differences between 2 groups among the three groups. When the difference between groups were not significant in the Kruskal Wallis test, the pre-post treatment change in scores was calculated, and the percentage of changes in pre-post score was reported.

6.3 Results

The London site sample size for both HOLOBalance/HOLOBox and control groups was n= 14. Total number of participants n=54 (HOLOBalance n=12; HOLOBox n= 21; and control n=21), from the Athens and Freiburg sites further to the London site. Feasibility and acceptability data are presented only for the London site as these data may differ from other sites and the interviews were not conducted in English at the other sites. All data from all studies sites (n= 54) is included for the secondary analysis.

Recruitment occurred during the COVID-19 lockdown period and restrictions were in place including limited face-to-face meetings. The COVID-19 global pandemic affected continuous recruitment and introduced uncertainty for recruitment due to the various government restrictions imposed across the three study sites.

In total, 66.7% of participants were female and 50% had experienced one or more falls during the previous year. No between-group differences were noted for age, sex, sociodemographic and clinical (balance and gait function) characteristics at baseline. The number of participants allocated to each intervention at each of the three sites is demonstrated in Table 6-4.

Site	HOLOBalance	HOLOBox	Control	Total
Athens	6	10	10	26
Freiburg	2	6	6	14
London	4	5	5	14
Total	12	21	21	54

Table 6-4 Number of participants in each group in each site and intervention.

6.3.1 Feasibility and acceptability

6.3.1.1 Recruitment, dropout, and completion rates

Recruitment occurred between April 2021 to October 2021. Among the 21 volunteers who were screened, 14 (67%) were eligible and all were enrolled. Volunteers were excluded (n=7) because the MoCA score was below the cut-off score (n=2), were not at risk of falls (FGA ≥ 22/30), did not report a fear of falling (FESI short form <10) or had not experienced a fall/s in the last 12 months) (n=5).

The research protocol was successfully delivered to all participants, and the outcome assessor remained blinded to the intervention throughout the study duration. The completion rate was good as defined from adherence rate and the number of missing sessions from the system. Of the enrolled participants, the adherence rate to the programme was 2 participants (50%) in the HOLOBalance and 4 participants (80%) in the HOLOBox completed the 8-week intervention program. The average of compliance to exercise was 45 minutes per day of intervention for 8 weeks.

One participant from the HOLOBalance completed only 6-weeks. On participant withdrew in each group as follow: one participant from the HOLOBalance group due to a personal issue not related to the study, one participant from the HOLOBox group due to difficulties in attending the sessions at KCL and using public transport during COVID-19 pandemic, and one participant from the control group after developing severe dizziness after week 2 (session 5). The control group received the Otago programme which does not include any vestibular potentially dizziness inducing exercises. The participant was followed up and reported that the dizziness subsided two weeks after withdrawing from the programme. Consort Diagram for HOLOBalance feasibility study is illustrated in Figure 6-6.

6.3.1.2 Safety

No serious-adverse events were recorded in the intervention HOLOBalance/HOLOBox group.

6.3.1.3 Acceptability

Acceptability of the HOLOBalance and HOLOBox intervention was determined from the interview feedback.

6.3.1.3.1 Thematic analysis from the semi structured interview of the HOLOBalance group

Participants signed up for the study to discover new rehabilitation techniques. The HOLOBalance motivated patients to complete their exercises at home and they noted that their balance improved after completing the program. The most favourite exercises were standing on foam, walking exercises with head turns in the exergames, and catching the apples and the card memory cognitive games. A participant acknowledged improvement and stated that he “was able to walk up the stairs more quickly without holding the handrail” another participant stated that “the system helped me to move and do the exercise at home in my convenient time”.

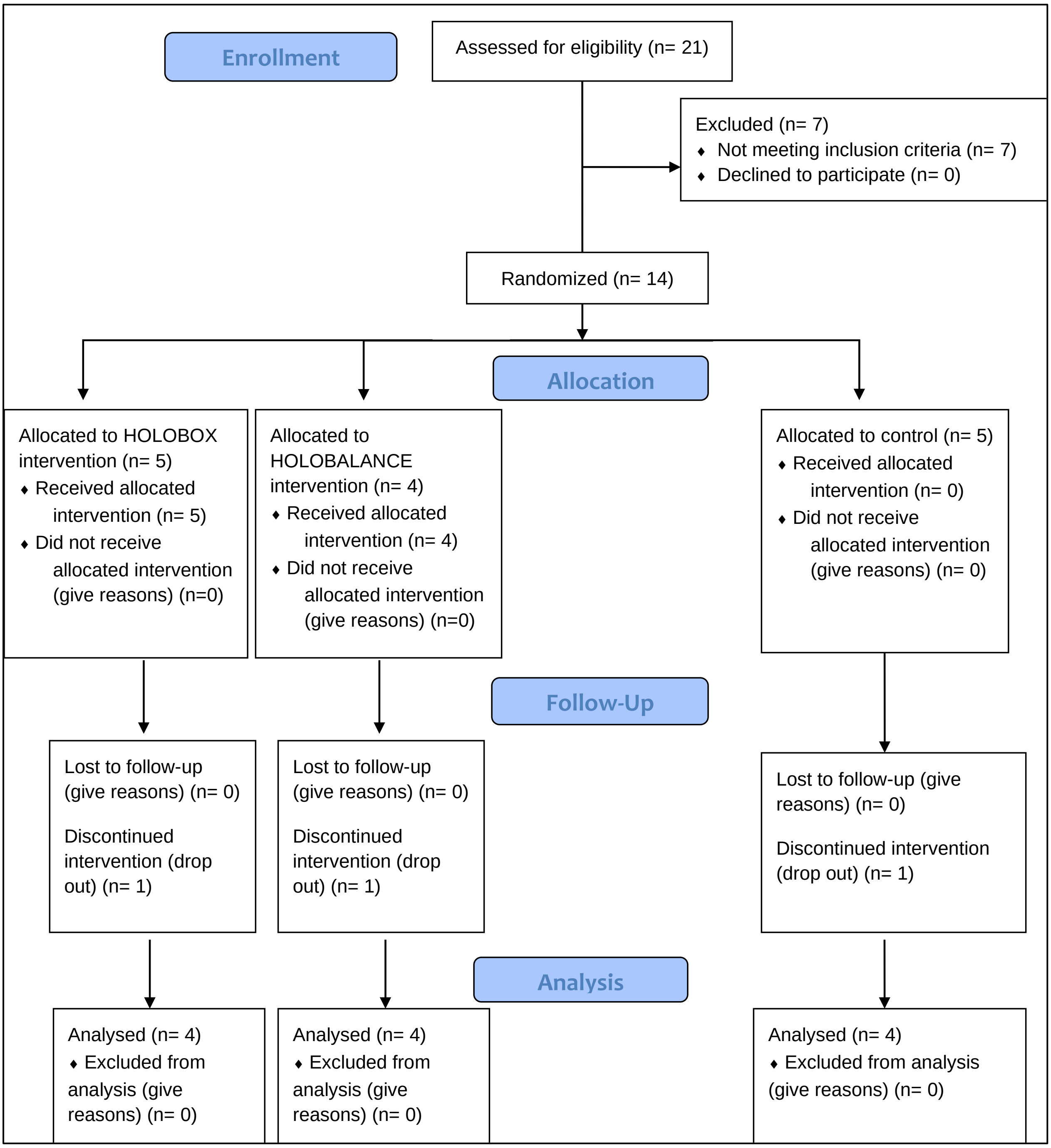


Figure 6—6 Consort Diagram for HOLOBalance feasibility study for older adults for recruitment from London site.

Problems reported were specific to technical difficulties, including the need to wear the sensors before starting the exercise session and charging insole batteries. Further technical challenges reported were difficulty in maintaining the Head-mounted Device stable while performing the exercises and the system shutting down without any prior notification, which participants commented increased their frustration level.

6.3.1.3.2 Thematic analysis from the semi structured interview of the HOLOBox group

Participants in HOLOBox intervention group stated that the reason for participation was to improve strength, balance and to discover new rehabilitation techniques. Participants appreciated their improvement in balance control after completing the programme, and they reported that the exercises helped in their ability to perform daily activities such as standing on uneven surfaces. One participant commented that she "was able to walk with more confidence in the community settings and in busy areas better", another participant stated, "I feel I am more focused while walking outside and can walk for longer distance in a walking group, and not feeling wobbly".

The most favourite exercises from all categories were standing on foam, walking exercises with head movement for MSR and exergames exercises, and catching the apples game from the cognitive games. Similar to the HOLOBalance group, participants in HOLOBox group considered the component which helped in cognitive skills was the card memory game. The least favourite part of the hardware was the Head-mounted Device. Participants found it frustrating when they could not start the exercise after the instructions directly, however the system required some time to connect to the signals from body attached sensors.

6.3.1.4 System Usability Scale

In the HOLOBalance group, of the two participants interviewed rated the acceptability of the system as very low. In the HOLOBox group, 2 participants had a score above 70 which shows "good" acceptability of the system. The standard scores are presented in Table 6-5.

6.3.1.4.1 The User Experience Questionnaire

Participants in the HOLOBalance intervention (HOLOBalance home and HOLOBox) rated the system as understandable in the perspicuity part of the User Experience Questionnaire. In the HOLOBalance group, one participant rated it as efficient, but other items from the User Experience Questionnaire (attractiveness, dependability, stimulation, and novelty) were rated with a score of 1 or below out of 7, which indicates a positive attribute. Most participants in the HOLOBox intervention rated the system with a score of 2 out of 7 for attractiveness, perspicuity, and efficiency which indicates moderate positive attributes. For the dependability, stimulation, and novelty most participants rated with a score of 3 out of 7 which indicates the maximum positive attributes.

Intervention group	**Participant**	**SUS score**
HOLOBalance group	HH1	15
	HH2	10
HOLOBox group	HB1	75
	HB2	62
	HB3	30
	HB4	90

Table 6-5 Scores of the System Usability (SUS) Scale in HOLOBalance (HH) and HOLOBox (HB) groups.

6.3.1.4.2 The NASA Task Load Index

Participants in HOLOBalance and HOLOBox groups rated the system with a score of below 15 indicating no high mental, physical, or temporal demands. Similarly, the level of performance, effort and frustration were 15 or below (out of 21), presented in Table 6-6.

Intervention group	Participant	Mental demand	Physical demand	Temporal demand	Performance demand	Effort demand	Frustration
HOLOBalance group	HH1	10	12	4	10	9	15
	HH2	11	11	15	12	12	16
HOLOBox group	HB1	10	8	7	7	7	7
	HB2	10	14	5	12	12	12
	HB3	10	10	7	14	14	14
	HB4	16	11	9	7	10	10

Table 6-6 The NASA Task Load Index for the HOLOBalance and HOLOBox groups.

6.3.2 Physical assessment

6.3.2.1 Balance assessment (Mini-BESTest)

The results of the Mini-BESTest in each group are presented in Table 6.7. A significant between-groups difference was noted, $\chi^2(2) = 11$, $p<0.004$. Post hoc analysis with Mann-Whitney U test showed a significant difference between both HOLOBalance and HOLOBox with the control group.

HOLOBalance group (mean rank = 16.5) were significantly higher compared to the control group (mean rank = 8.64), U = 16, z = -2.76, (p < 0.006). HOLOBox group (mean rank = 19.5) were significantly higher compared to the control group (mean rank = 10.93), U = 48, z = -2.68, (p < 0.007). No difference was noted between the HOLOBalance and HOLOBox groups. Figure 6-7 illustrates the difference between all groups.

Treatment group	**Period**	**n**	**Min- Max**	**Mean ± SD**
HOLOBalance	pre	12	15- 24	19 ±2
	post	8	15 - 25	23 ±3
HOLOBox	pre	20	11 -24	18 ±3
	post	16	16 -25	21 ±3
Control	pre	20	6 - 23	16 ±4
	post	14	11- 25	18 ±4

Table 6-7 Means ±SD for the Mini Balance Evaluation System Test (Mini-BESTest) in each treatment group. Sample size (n).

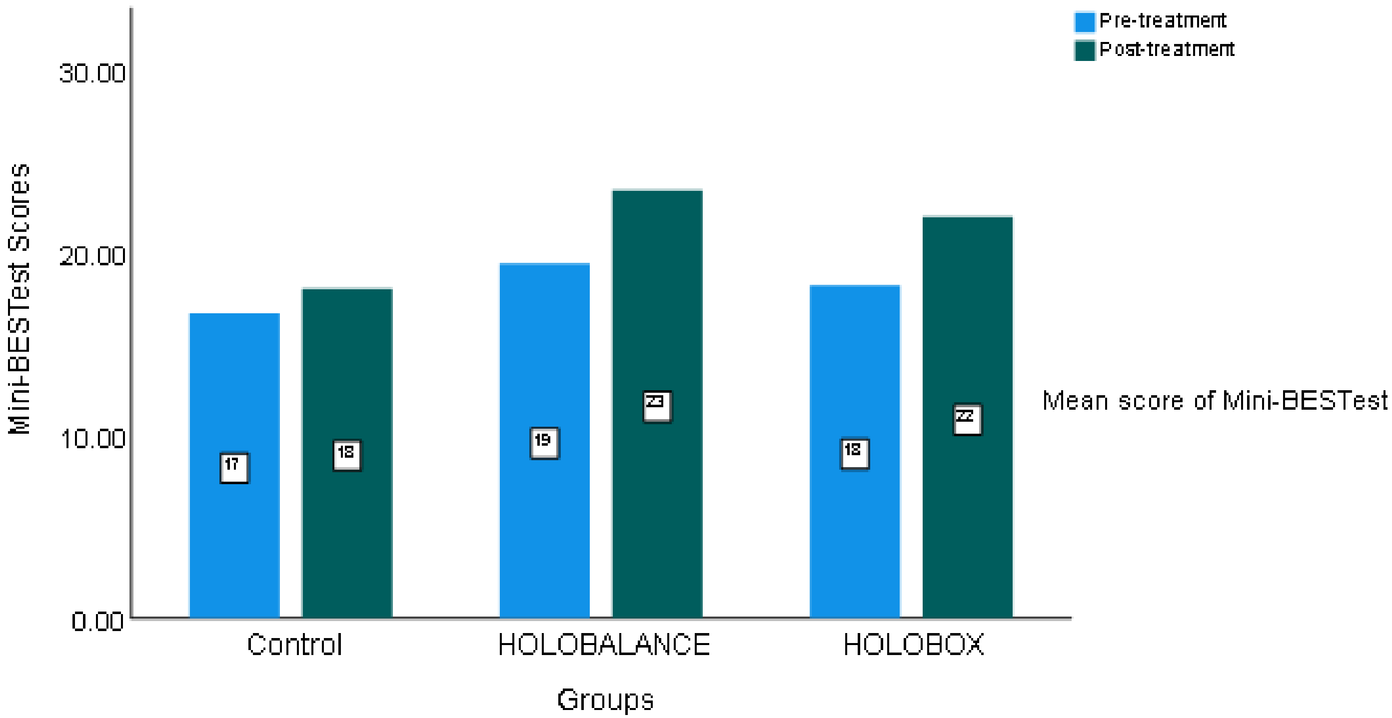


Figure 6—7 Mean score of Mini-Balance Evaluation System Test (Mini-BESTest) pre- and postintervention for all groups.

6.3.2.1.1 Functional gait assessment

A significant between-groups difference was noted in Kruskal Wallis Test $\chi^2(2) = 8.4$, ($p < 0.01$). Post hoc analysis with Mann-Whitney U test showed a significant difference between both HOLOBalance and HOLOBox with the control group, HOLOBalance group (mean rank = 16.88) were significantly higher compared to the control group (mean rank = 9), U = 21, z = - 2.53, ($p < 0.01$). HOLOBox group (mean rank =19.97) were significantly higher compared the control group (mean rank = 12.57), U = 68, z = - 2.24, ($p < 0.02$). No difference was noted between the HOLOBalance and HOLOBox groups. Table 6-8 presents the data; Figure 6-8 illustrates the difference between all groups.

Treatment group	**Period**	**n**	**Min- Max**	**Mean ±SD**
HOLOBalance group	pre	12	14-24	19 ±4
	post	8	14-29	24 ±5
HOLOBox group	pre	21	8-26	18 ±4
	post	17	12-30	23 ±5
Control group	pre	21	8-25	17 ±3
	post	15	14-25	20 ±3

Table 6-8 Means ±SD for the Functional Gait Assessment (FGA) pre and post intervention in each treatment group.

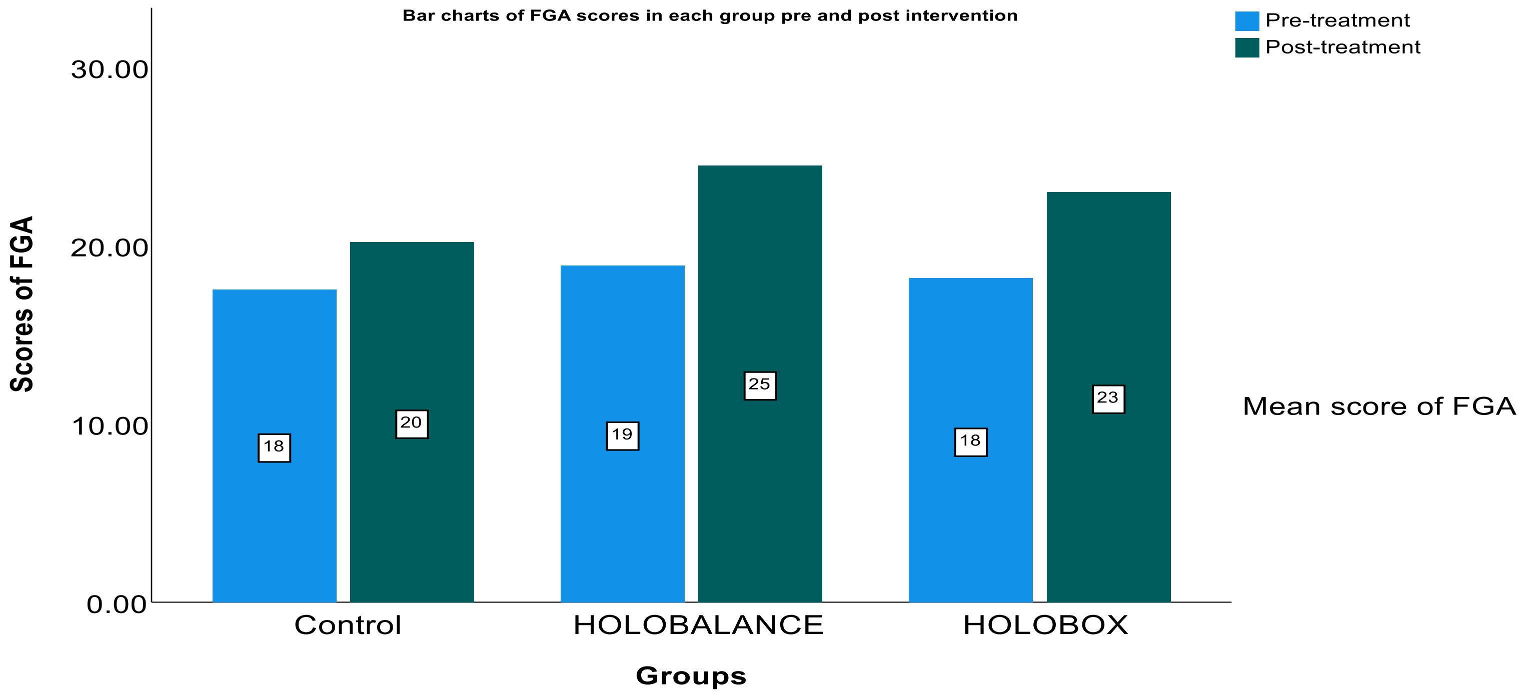


Figure 6—8 Mean score of Functional Gait Assessment (FGA) for pre- and postintervention for all groups.

6.3.3 Cognitive assessment

The CANTAB test scores and the pre-post treatment score changes are presented in Table 6-9 to 6-11. No between-groups difference was noted. The pre-post score changes in latency (time duration) between pre and post intervention is decreased (i.e., better) ≥15 in the motor screening test, Multitasking test, and Rapid Visual Information Process tasks in all three groups. In addition, a decreased (i.e., better) ≥15 in latency was noted in Reaction Time task in the HOLOBox group.

The CANTAB test	Initial assessment			Final assessment			Score change	
	n	Min- Max	Mean ±SD	n	Min-Max	Mean ±SD	Min-Max	Mean ±SD
MOT	9	860-1968	1075 ±349	5	682-1800	1018 ±461	-285-490	71 ±318
PAL	9	7-45	23 ±16	5	3-43	20 ±19	-11- 36	4 ±18
SWM	9	4-17	12 ±4	5	0-16	7 ±7	-14- 5	-4 ±7
RTI	9	151-536	315 ±114	5	268-389	322 ±47	-206- 169	14 ±159
DMS	9	60-100	82 ±12	5	40-100	68 ±27	-40- 20	-12 ±23
MTT	9	117- 566	376 ±122	5	-224 - 351	102 ±263	-605 -113	-217 ±327
PRM	9	55-100	79 ±15	5	67-100	84 ±14	-28 -33	11 ±23
RVIP	8	371- 855	522 ±148	5	388- 660	519 ±120	-155 -288	42 ±181

Table 6-9 The results from CANTAB tests in the HOLOBalance group, minimum- maximum scores, mean ±SD of scores and the means of score change. Motor Screening test (MOT), Paired Associated Learning (PAL), Spatial Working Memory (SWM), Reaction Time (RTI), Delayed Matching to Sample (DMS), Multitasking test (MTT), Pattern Recognition Memory (PRM), Rapid Visual Information Process (RVIP). Sample size (n).

The CANTAB test	Initial assessment			Final assessment			Score change	
	n	Min- Max	Mean ±SD	n	Min-Max	Mean ±SD	Min-Max	Mean ±SD
MOT	16	698-1361	990 ±207	13	702-1421	911 ±185	-336- 615	-43 ±238
PAL	19	5-60	30 ±16	13	9-36	23±16	-26- 15	-6 ±12
SWM	19	0-23	13 ±5	13	9-21	15 ±3	-6- 14	1.6 ±5.6
RTI	19	120-502	331 ±84	13	273-436	341 ±50	-76- 21	20 ±72
DMS	19	40- 100	65 ±16	13	20-100	74 ±21	-60- 40	9 ±25
MTT	19	-86 -774	280 ±257	13	-31 -591	252 ±189	-543 -384	-80 ±279
PRM	19	44-100	79 ±15	13	39-100	78 ±17	-61 - 22	-5 ±22
RVIP	19	380- 1317	633 ±247	13	373 - 1117	609 ±225	-502 - 158	-35 ±160

Table 6-10 The results from CANTAB tests in the HOLOBOX group, minimum- maximum scores, mean ±SD of scores and the means of score change. Motor Screening test (MOT), Paired Associated Learning (PAL), Spatial Working Memory (SWM), Reaction Time (RTI), Delayed Matching to Sample (DMS), Multitasking test (MTT), Pattern Recognition Memory (PRM), Rapid Visual Information Process (RVIP). Sample size (n).

The CANTAB test	Initial assessment			Final assessment			Score change	
	n	Min- Max	Mean ±SD	n	Min-Max	Mean ±SD	Min-Max	Mean ±SD
MOT	18	650-3035	1180 ±532	10	587-1098	844 ±189	-570-125	-135 ±226
PAL	19	3-53	33 ±14	10	15-56	32 ±11	-16- 26	-2 ±13
SWM	19	7-19	14 ±3	9	4-18	12 ±5	-7- 3	-1 ±4
RTI	19	192-661	363 ±116	10	241-591	351 ±104	-110- 161	7 ±97
DMS	19	20-100	69 ±21	9	60-100	75 ±13	-40- 60	7 ±30
MTT	19	-10 - 701	292 ± 227	9	105- 571	323 ±156	-428 - 513	-56 ±260
PRM	19	55-100	81 ±10	10	55- 83	73 ±10	-22 -11	-7 ±11
RVIP	18	255- 933	631 ±173	9	514- 981	714 ±159	-125- 358	47 ±164

Table 6-11 The results from CANTAB tests in the control group, minimum- maximum scores, mean ±SD of scores and the means of score change. Motor Screening test (MOT), Paired Associated Learning (PAL), Spatial Working Memory (SWM), Reaction Time (RTI), Delayed Matching to Sample (DMS), Multitasking test (MTT), Pattern Recognition Memory (PRM), Rapid Visual Information Process (RVIP). Sample size (n).

6.3.4 Subjective assessment for psychosocial aspects

The mean ±SD and the changes in scores for the questionnaires for HOLOBalance, HOLOBox and control groups are presented in Table 6-12 to 6.14 respectively. No between-group difference was noted in all subjective assessments.

However, in pre-post intervention score changes in the Activities-specific Balance Confidence Scale were noted in the HOLOBalance group, there was increased (i.e., better) change in 8 points compared to the other groups. Also, in the WHO Disability Assessment Schedule 2.0, the HOLOBalance group had the greatest decrease (i.e., better) in 7 points.

The greatest decreased (i.e., better) pre-post intervention score changes in the Behaviour regulation in exercise questionnaire-3 in 7 points was noted in the HOLOBox group. The pre-post intervention score changes for the Rapid Assessment of Physical Activity scale, Falls Efficacy scale International were below 5 points for all groups.

Self-rated questionnaires	Initial assessment			Final assessment			Score change	
	n	Min-Max	Mean ±SD	n	Min-Max	Mean ±SD	Min-Max	Mean ±SD
ABC scale	5	46- 96	81 ±20	5	81- 97	89 ±5	-4- 35	8 ±15
WOHDAS	5	0-30	17 ±11	5	3- 25	9 ±9	-27- 7	-7 ±15
RAPA	5	0-9	6 ±4	5	7- 10	7 ±1.5	0-7	2 ±3
FESI	5	19-45	25 ±11	5	17- 27	21 ±5	-18- 5	-4 ±8
BREQ-3	5	11- 58	24 ±19	5	3- 78	28 ±29	-8- 20	4 ±10

Table 6-12 The results of self-rated questionnaires, minimum- maximum scores, mean ±SD of scores and the means of score change in the HOLOBalance group. Activities-specific Balance Confidence (ABC) scale, The World Health Organisation Disability Assessment Schedule (WHODAS), The Rapid Assessment of Physical Activity (RAPA) scale, Falls Efficacy (FESI) scale and Behaviour regulation in exercise questionnaire (BREQ-3). Sample size (n).

The CANTAB test	Initial assessment			Final assessment			Score change	
	n	Min-Max	Mean ±SD	n	Min- Max	Mean ±SD	Min- Max	Mean ±SD
ABC scale	12	21- 97	73 ±23	12	30-98	78 ±24	-18 -20	5 ±11
WOHDAS	12	1- 34	7±9	12	1-16	5 ±5	-19- 7	-2 ±6
RAPA	7	2- 9	6 ±2	7	2-9	5.7 ±3	-3- 2	-0.5 ±2
FESI	12	17- 42	27 ±8	12	17-45	25 ±9	-17- 9	-1 ±7
BREQ-3	12	0.30- 79	28 ±26	12	-11- 81	21 ±23	-76- 12	-7 ±23

Table 6-13 The mean ±SD of self-rated questionnaires and the means of scores changes in the HOLOBOX group. Activities-specific Balance Confidence (ABC) scale, The World Health Organisation Disability Assessment Schedule (WHODAS), The Rapid Assessment of Physical Activity (RAPA) scale, Falls Efficacy (FESI) scale and Behaviour regulation in exercise questionnaire (BREQ-3). Sample size (n).

The CANTAB test	Initial assessment			Final assessment			Score change	
	n	Min-Max	Mean ±SD	n	Min-Max	Mean ±SD	Min- Max	Mean ±SD
ABC scale	7	50- 98	78 ±17	7	65- 98	85 ±11	-3- 36	7 ±13
WOHDAS	7	1-12	6 ±5	7	0- 12	4 ±4	-10- 4	-2 ±5
RAPA	3	3- 8	6 ±2	3	4- 8	5 ±2	4-8	5 ±2
FESI	7	18-56	28 ±13	7	17- 35	22 ±6	-7- 5	-2 ±4
BREQ-3	7	-1- 64	18 ±22	7	-7- 72	21 ±25	-11- 19	3 ±10

Table 6-14 The mean ±SD of self-rated questionnaires and the means of scores changes in the Control group. Activities-specific Balance Confidence (ABC) scale, The World Health Organisation Disability Assessment Schedule (WHODAS), The Rapid Assessment of Physical Activity (RAPA) scale, Falls Efficacy (FESI) scale and Behaviour regulation in exercise questionnaire (BREQ-3). Sample size (n).

6.4 Discussion

Provision of balance rehabilitation by means of information and communication technologies and digital solutions is a rapidly evolving field (696,697). The recent Covid-19 pandemic expedited these developments, such as remote assessment and management of patients with balance disorders and falls, which is now mandatory standard practice (698). These technologies provide the means for multifaceted truly individualised rehabilitation but require evaluation for feasibility, acceptability, safety, and effectiveness prior to their implementation in clinical practice.

This is a randomised controlled study to assess the feasibility and acceptability of augmented reality (AR) delivered balance training through the HOLOBalance system, sensor based monitored with real time feedback MSR and cognitive exergames. The HOLOBalance platform offers motivation with the use of holograms, gamification of exercises and objective recording of the exercise performance at the most detailed level possible. It used sensors to capture movement and provide details about maximum and average speed and proximity to participant's movement the pattern (376).

The first iteration of the platform demonstrated that it was both feasible and acceptable to users. Trends in improvement in balance and gait were observed, as well as in balance confidence and in disability assessment in the HOLOBalance/HOLOBox group. However, no difference was observed in cognitive function and psychosocial symptoms in any group. Findings will be discussed in more detail in the paragraphs below.

6.4.1 Feasibility and acceptability of the HOLOBalance system

The feasibility and acceptability study from the London site met all the protocol criteria. Drop-out rate was low in the HOLOBox group; however, it was greater in the HOLOBalance group as a result of difficulty relating to handling the equipment at home.

No serious adverse effects were reported for all interventions, indicating that the HOLOBalance/HOLOBox system for balance training was safe for older adults at risk of falls. Despite the complexity in the preparation process prior to starting the exercises in each session with the HOLOBalance/HOLOBox, the adherence to exercise was high. The interview results showed that participants' overall experience was positive, however, some difficulties in dealing with the devices (such as wearing the sensors and keeping the Head-mounted Device stable while performing the exercises) were mentioned. This is in general agreement with previous studies on telerehabilitation, where poor digital literacy is common in older adults with mild cognitive dysfunction (66,68). The difficulty relating to telerehabilitation may be attributed to the requirement for participants to complete assessments, adhere to the exercise intervention, execute the exercises, and manage the wearable devices and monitoring system (699). However, the use of technology to improve health has been recommended as a method to increase evidence-based information on telerehabilitation (700).

The usability of the system was good for both HOLOBalance at home and HOLOBox in the laboratory setting, albeit there is a variation because participants in the HOLOBox group had direct immediate help during the sessions, which affected the usability scores. A previous study showed that the usability of the COCARE system was reported as good, which was also assessed by the System Usability Scale (355). However, in the COCARE system, only a few exercises were added from standing, and very simple cognitive tasks such as pressing the same colour seen on the screen with no direct feedback were provided from the system. The HOLOBalance system consists of MSR exercises targeting the needs of older adults at risk of falls with more advanced exercises such as walking while simultaneously turning one's head, in addition to challenging exergames to stimulate attention and spatial memory. It can be suggested that HOLOBalance home users have a concurrent video conferencing to help in guiding them through the process and providing technical support if needed to enhance the usability of the system. In addition, the forthcoming version of the HOLOBalance system will have four IMU sensors located at the head, lower back, and ankles in place of the insoles and fewer body sensors. It will also have a lighter headset which offers similar AR experience.

6.4.2 Balance and functional gait

Trends of improvements in balance and functional gait were greater in the HOLOBalance and HOLOBox groups compared to the control group, which is in line with the hypothesis. The MSR exercises are aimed at addressing multiple components of balance, including vestibular function, movement strategies, visual spatial orientation and muscle strengthening exercises. The improvements in balance and gait in the current study are similar to previous work have indicated improvement in balance and gait after the MSR exercises (326–329).

Additionally, the current results are in agreement with a previous systematic review by Lee et al (2023) on telerehabilitation systems, using smartphones or tablets to provide biofeedback, exercises for flexibility, strength, balance and gait, or video games, at home or in a community centre, and found similar results (346). Lee et al (2023) review's reported functional movements (i.e., Mini-BESTest, and Dynamic Gait Index), cognition function (i.e., MoCA), and reduced fear of falling and anxiety levels (i.e., the average Beck Anxiety Inventory) after the intervention period, the intervention duration in the selected studies ranged from 6 to 12 weeks (346). However, in the COCARE system, only the feasibility, acceptance and enjoyment were assessed after one session; balance control and functional motor performance were not assessed.

In the current feasibility study, balance and gait were assessed by clinical tests based on performance observation. However, there is a need for more objective balance and gait assessments, for example, with the force plate (559) and/or Vicon system (560), which provide more valid comprehensive quantitative data. In addition, more objective muscle tests such as with electromyography (EMG) to measure muscle response or electrical activity in response to a nerve's stimulation of the muscle and to help compare neuromuscular abnormalities before and after the intervention should be included (600).

6.4.3 Adherence to HOLOBalance programme

Participants in the HOLOBox group demonstrated very good adherence rates (80%), while adherence in the HOLOBalance programme was lower (50%) due to the difficulty in dealing with the equipment. An overview by Collado-Mateo et al (2021), which included 55 systematic reviews and 11 meta-analyses, identified a number of relevant and key factors to increase adherence to physical exercise including: the usefulness of exercise, enjoyment added by the use of technology, support, participants' education, and communication and feedback (701). The use of technology adds enjoyment to the exercise; however, participants at home may have difficulty learning digital requirements and need support in dealing with the equipment.

For future studies, a family member or carer could be trained to offer help when needed, which will help in increasing the adherence rates for using telerehabilitation at home.

6.4.4 Adherence to home exercises

Participants' adherence to home exercises in the HOLOBox group was overall very good and this is reported to help improve balance and functional gait scores (692). This is in agreement with previous studies which have indicated that home exercises help in increasing independence (683) and physical activity in older adults at risk of falls (690). Additionally, adherence to home exercises can help to improve behavioural strategies and self-efficacy (702).

6.4.5 Cognitive training

Cognitive training and exergames included in the intervention groups may have also contributed to the improvement noted in dynamic balance and functional gait compared to the control group. This must be confirmed in a full-scale study, but current results provide a strong indicator of efficacy that supports the justification for a full-scale randomised controlled trial.

An experimental study by Lehmann et al (2022) found that there is a relationship between cognitive function and balance control in older adults compared to young adults; in which higher-order cognitive function such as executive functions were in demand while walking only in older adults (703). A recent study by Lehmann et al (2022) found that in older adults, the superior frontal gyrus was activated in balance performance tests but not in young adults

(703). These few studies indicate the importance of cognitive changes in older adults, and their association with balance control.

Another trial by Smith-Ray et al (2015) recruited 51 older adults and found that adding computer-based intervention for cognitive training for 10 weeks had a significantly greater impact on balance and gait (assessed by 10-m walk test, and gait speed with cognitive distraction) than without cognitive training (704). The cognitive training in the Smith-Ray et al (2015) study was performed to train executive functions, including visuospatial working memory and speed of processing (704). Cognitive training and exergames implemented in the HOLOBalnce system targeted both cognitive function (visuospatial working memory and speed of processing), and in the exit interview, participants revealed that the cognitive training was useful.

In the current study, mild improvement was observed in the average score after the HOLOBalance/HOLOBox intervention in certain cognitive tests including the Motor Screening test, Multitasking test, and Rapid Visual Information Process tasks. The type of cognitive training implemented in the HOLOBalance/ HOLOBox programme may have contributed to the improvements noted, but the duration was about 10-15 minutes daily for 3-4 weeks. There is some evidence suggesting that simultaneous cognitive and exercise training, may provide more improvements compared to cognitive training alone or cognitive training practised after physical training (705–707). Additionally, for older adults with mild cognitive impairments, improvement in cognitive function can be gained after 1-hour training twice a week over 6 months (708).

Most assessments in previous studies were limited to the Trail Making Test for visual attention, and working memory was assessed with the Executive Control Task (709). However, due to the difficulty in the CANTAB tests, participants might demonstrate a floor effect (710).

A study on CityQuest intervention, which aimed to train typical, everyday multisensory processes including sensory-motor control, spatial navigation, obstacle avoidance and balance control for older adults, showed that structural cerebral changes occurred for those who successfully completed the five-week intervention. A grey-matter volume increase in the precentral gyrus, and grey-matter volume reduction in the inferior temporal and orbitofrontal gyri were observed in all participants. Furthermore, a greater grey-matter volume increase in the precentral gyrus was observed in participants who performed the full CityQuest intervention relative to those required to avoid obstacles only (711). Cognitive training can be recommended in addition to physical balance exercises for optimal balance control in older adults.

6.4.6 Psychosocial and participation factors

From the self-rated questionnaires, the HOLOBalance group showed a tendency for improvement in both the balance confidence scale (i.e., Activities-specific Balance Confidence Scale) and the disability assessment (i.e., WHO-Disability Assessment Schedule). Similarly, in the HOLOBox group, there was an improvement in the score change in the behaviour to exercise questionnaire. Although self-rated questionnaires may be influenced by subjective bias, the pre-post treatment score differences were within the minimum detectable change for the specific OM (554,695,712). A recent systematic review showed that balance training with MSR exercises helped improve balance confidence (383). However, there are no previous studies on the association between MSR exercises and disability assessment and behaviour to exercise (such as internal facilitators and barriers).

6.4.7 Limitations of the study

Study limitations included the limited duration for recruitment and the small sample size. Recruitment occurred during the COVID-19 lockdown with government restrictions for research at all clinical sites. Multicentre studies provide larger sample sizes, however, differences in personal and population characteristics might exist, which may increase heterogeneity (713,714).

In addition, sampling bias might exist since sampling was based on a convenience method which might not reflect the general population. The findings may not represent the entire older adult population, which might limit the generalisability. The HOLOBalance system was limited to older adults with no or mild cognitive dysfunction because of the level of cognitive training and auditory tasks, making it not applicable for older adults with moderate or severe cognitive impairments.

Participants in the HOLOBalance group experienced technical difficulties, for example, in wearing and charging the sensors, especially for the insole sensors. This can provide insights suggesting future iterations use fewer wearable sensors or ones which area easier to use.

Meanwhile, data for the feasibility and acceptability were reported from the London site only since the interviews were not in the English language in the other centres and due to lack of interpreters. Semi-structured exit interviews were used to assess acceptability; however, the interviews would be enriched if conducted by an external assessor to improve external validity.

Furthermore, balance and gait performance were assessed by clinical tests based on performance observation, which are subjected to biases and lack more thoroughly objective measurement, such as with a force plate system (559), or Vicon (560), which provide more comprehensive data. The assessment for secondary aims was limited to pre- and post-treatment assessment; a follow up assessment would help in identifying the trends in improvement earlier and determine whether modifications are required. Additionally, a follow up assessment after the end of intervention to record falls was limited to 3 months only, which limits the assessment of long-term incidence.

Furthermore, the statistical analysis for the secondary outcomes were based on non-parametric tests because of the small sample size and non-normal data distribution which was considered less powerful than the parametric tests (595).

6.4.8 Recommendations for further studies

Further studies with larger samples are important. Additionally, to increase the usability of the system, the utilisation of fewer wearable sensors is recommended. Potential solutions or adaptations for older adults with varying degrees of tech-savviness might include a video explaining the process and steps for beginners or a worksheet in addition to the pictorial guide. Furthermore, providing a training workshop for participants on using devices would provide a complete picture of the intervention process, in addition to video conferences when participants need more support.

The assessment of balance and gait could include more objective measurement to provide more comprehensive data. Additionally, the assessment of cognitive-motor interference by dual-task walking tests will help in understanding the benefits of adding cognitive tasks and identifying the level for intervention needed for each participant. A follow-up assessment, for example, after 4 weeks from the initial assessment, can help in identifying the progression. Importantly, a follow-up period of more than 3 months to assess the sustainability of improvement after the intervention period should be included.

6.4.9 Implications for clinical practice

This study was a feasibility study, which is phase I in clinical trials. One of the important aspects of feasibility studies is to identify challenges to help further clinical research (715). The findings in this feasibility study for the acceptability and usability of the HOLOBalance support future larger research to encourage the use of telerehabilitation to improve activity and reduce the risk of falls in older adults. With the growing number of ageing and frail individuals, the implementation of telerehabilitation to help in improving balance and reduce the risk of falls is recommended by the British Geriatric Society guidelines (65). A few points were noted for clinical practice, including that the use of technology can increase patients' motivation and enjoyment, which helps in increasing adherence to exercise. Some mitigations are needed to increase the usability of the system, such as using fewer wearable sensors and providing simultaneous technical support if needed.

Trends of improvement in balance and functional gait for older adults at risk of falls were noted in the intervention group that received the HOLOBalance/HOLOBox system which includes MSR exercises, cognitive, and auditory tasks. This indicates the importance of MSR exercises in improving the vestibular function in older adults (327,329,383,716). Additionally, adding exergames, cognitive and auditory tasks for older adults even with no or mild cognitive impairments, is recommended to reduce the risk of falls (616,655,656,667). Stimulating the vestibular system and cognitive function is essential to improve optimal balance control and functional gait, which needs to be implemented in regular balance rehabilitation for older adults at risk of falls.

In general, the potential broader impact of telerehabilitation is increasing. Telerehabilitation can provide easier access to rehabilitation, especially for people living in remote areas, enhancing their compliance to exercise programmes in a sustainable manner (717). Additionally, telerehabilitation can improve collaboration between professionals to build interprofessional telehealth (718).

6.4.10 Conclusion

Preliminary findings from this study support the feasibility and acceptability of the HOLOBalance/HOLOBox system for balance training for older adults at risk of falls. The exit interviews reveal that participants enjoyed exercises using the system; however, technical difficulties were noted for HOLOBalance home users. Future studies should consider how to minimise technical difficulties. Functional gait and balance training with MSR exercises, and exergames for cognitive training showed trends towards improvement in the HOLOBalance/HOLOBox groups. Findings support further investigation of the HOLOBalance system as a telerehabilitation solution for balance training in older adults at risk of falls in a fully powered randomised controlled trial.

Chapter 7: Feasibility of the HOLOBalance System for Balance Training for Stroke Survivors

7.1 Introduction

The feasibility of the HOLOBalance intervention protocol in older adults at risk of falls has been reported in the previous chapter. The system was feasible and acceptable to provide balance training for older adults at risk of falls and the adherence rate to exercises was good and a low dropout rate was reported. Trends of improvement in balance and functional gait, in addition to increased (i.e., better) scores of balance confidence were observed in both HOLOBalance/ HOLOBox groups. An individualised assessment and rehabilitation programme to improve balance and reduce fall risk for stroke survivors is recommended by the NICE UK Guidelines 2023 (719). However, previous studies have shown that adherence to balance and gait exercises is poor in stroke survivors (720,721). Recently, studies have suggested that telerehabilitation may help to improve adherence to exercise in stroke rehabilitation (71,722).

A systematic review of 31 studies by Chen et al (2019) for home-based technologies (telerehabilitation (n=8), games such as Nintendo and Wii sports (n=14), virtual reality devices (n=6), tablets (n=2), sensors (n=4) and robotic devices (n=7)) for stroke rehabilitation indicated that home-based technologies helped increase the engagement in exercising, including external and internal motivation (340). Additionally, Chen et al (2019) reported that 23 studies, from the included 31 studies, showed improvement in motor skills (i.e., Barthel Index, and Berg Balance Scale (BBS)) after an average 8-weeks of intervention (340). However, Chen et al's (2019) review identified that studies on telerehabilitation for stroke survivors were more focused on the upper limb and the exercises were general and not specific according to patients' needs.

Rehabilitation of balance and functional gait for ambulatory stroke survivors commonly includes simple exercises such as sit to stand and does not cover the entire elements of impairments and limitations induced by a stroke (36). All balance components, including the vestibular system and cognitive function, should be addressed for balance rehabilitation (40); however, few studies in stroke survivors include vestibular or multifactorial balance exercises (723,724). As the HOLOBalance system was feasible and acceptable in older adults at risk of falls, with improvements noted for dynamic balance and functional gait, it would be beneficial to assess its feasibility and acceptability in the stroke population. The HOLOBalance system may be a beneficial rehabilitation system for stroke survivors who experience balance difficulties and increased fall risk and should be investigated.

7.1.1 Study objectives

Primary objective: To investigate the feasibility and acceptability of implementing the supervised HOLOBalance intervention in the laboratory setting to ambulatory chronic stroke survivors.

Secondary objectives: To explore trends for effectiveness on physical, cognitive, and psychosocial aspects after the HOLOBox intervention for ambulatory chronic stroke survivors. Specific secondary objectives were:

i. To determine whether there are improvements in balance (Mini-Balance Evaluation Test) and gait function (Functional Gait Assessment (FGA)) after the intervention.
ii. To determine whether there are improvements in cognitive function (Cambridge Neuropsychological Test Automated Battery (CANTAB) tests) after the intervention.
iii. To determine whether there are improvements in subjective symptoms such as fears of falls (the Falls Efficacy Scale International) and balance confidence (the Activities-specific Balance Confidence Scale) and other subjective symptoms after the intervention.

7.2 Methods

An assessor-blinded feasibility study to explore the feasibility and acceptability of providing a supervised, laboratory-based balance HOLOBalance telerehabilitation programme delivered by a holographic projection to stroke survivors. Although, the HOLOBalance intervention is a telerehabilitation system, ultimately to be used in patient's homes, the feasibility of the system needs to be assessed in a laboratory setting via the HOLOBox to assess its feasibility and acceptability first and to ensure the safety management whilst in a safe and controlled environment.

In this feasibility study, data were collected at baseline and after the completion of an 8-week intervention. The flow of participants through the trial was recorded in compliance with the CONSORT statement (673,725).

7.2.1 The HOLOBalance programme

The HOLOBalance system deliver the balance training programme through the HOLOBox at the research laboratories of the Centre for Human and Applied Physiological Sciences, KCL. The treatment sessions were one hour for two treatment sessions per week for 8-week (16 in total), the initial and final assessments were at week-0 and week-10. Participants were required to complete a prescribed home exercise programme at home on the days that they were not attended the exercise session (i.e., 5 days a week), the same as the HOLOBox group for older adult at risk of falls protocol, described in Chapter 6, section "6.2.5.1 The active intervention: HOLOBalance (HOLOBalance HH or HOLOBox HB) balance rehabilitation group".

The study was approved by the KCL ethical board, reference number: HR/DP-21/22-26295, available in Appendix 32. Recruitment was done via advertisements placed through the Stroke Association, and via stoke community support groups in London, UK, from February 2022 to September 2022.

7.2.2 Participants eligibility criteria

Inclusion criteria were a) stroke survivors who experienced stroke more than 3 months ago; b) age 18 to 85 years; c) able to independently walk or walk with an assistive device; d) no significant visual impairment; e) able to understand and to consent to the research; f) no or mild cognitive impairment, a score of >22 on the MoCA test (http://www.MoCAtest.org/), g) willing to participate and to comply with the proposed training and testing regime; h) able to attend for the program at KCL for 10 weeks.

Exclusion Criteria were selected because of their potential impact on the outcomes and a screening questionnaire was completed by all volunteers. Exclusion criteria included presence of other neurological conditions (Parkinson's, peripheral neuropathy), acute musculoskeletal injury that prevents participation in a structured exercise programme (e.g., lower limb fracture), and/or unstable cardiopulmonary problems.

7.2.3 Intervention

The exercise programme is based on the MSR exercises protocols (327,328), described in Chapter 6 under section "6.2.5.1.3 The Multi-Sensory Rehabilitation (MSR) exercises". The cognitive and auditory training tasks are also described in Chapter 6, under section "6.2.5.1.7 Cognitive training" and section "6.2.5.1.8 Auditory training". The exercises were individually prescribed and progressed for each participant. Cognitive training exercises were initiated from week 4 to week 8. In addition, each participant was provided with the home exercise program from the printout MSR exercises (based on MSR exercises performed in the session) to do them on the days that they were not attending the sessions.

7.2.4 Outcome assessment

7.2.4.1 Primary outcomes

Primary outcome measures were acceptability and feasibility of providing the HOLOBalance system to ambulatory stroke survivors. Measures to explore acceptability are recruitment rate (% of eligible participants enrolled), adherence to exercise (% of completed exercise sessions) and drop-out rates (%). In addition, exit interviews were performed after completion of the HOLOBalance program. Thematic analysis was used to analyse the semi-structured exit interview, more explanation was presented in Chapter 4 (General Methodology), under section “4.5.1 Qualitative methodology approach for exit interviews”. The System Usability Scale (547), User Experience Questionnaire (548) and NASA task load index (549). All scales were described in Chapter 4 (General Methodology), under section “4.5.2 Assessment of feasibility, acceptability, and usability of the HOLOBalance system”.

7.2.4.2 Secondary outcomes

The Mini-BESTest (292,426,427), and the FGA (421) for balance and functional gait assessment, respectively. For cognitive assessment the validated Cambridge Neuropsychological Test Automated Battery (CANTAB) was used to assess the flowing tasks: Motor Screening, Match to Sample Visual Search, Paired Associates Learning, Reaction Time, Rapid Visual Information Process. All secondary outcome measures have been described in Chapter 4 (General Methodology), section “4.3 Assessment of physical, cognitive function and activity limitations”.

The subjective assessment for psychosocial factors were as follow, which all were described in Chapter 4 under sections “4.3.4 and 4.5.4 for the Self-rated questionnaires to assess activity and participation limitations”.

- World Health Organisation Disability Assessment Schedule (712)
- Activities-specific Balance Confidence scale (695)
- Falls Efficacy Scale International (551)
- Health-related Quality of Life questionnaire (726)
- The Behaviour regulation in exercise questionnaire (727)
- The Hospital Anxiety and Depression scale (728)

- Physical Activity Scale for Individuals with Physical Disabilities (506,629,729)
- Environmental Analysis of Mobility Questionnaire (Encounter and Avoidance) (250,516,617)
- Dizziness Handicap Inventory (510)

Falls diaries (730) were provided for participants to record any falls to the ground. They were also given an exercise log to record when they had practised the home exercise programme and any extra activity, they did on a specific day. Both the falls diary and exercise log were collected in week 10.

7.2.4.3 Baseline and final assessment

For the screening, potential participants were provided with a copy of the participant information sheet. All participant signed the consent form. The first test which was used as a screening to assess the level of cognitive function was MoCA test, a score of >22 (495,498) was used to identify mild cognitive impairments.

Demographic details (date of birth, height and weight, stroke onset and hemiplegia side) were recorded and all OM described in the previous section were completed at baseline and final assessment. The final assessment took place within one week after completing the 8-week exercise programme. In the final assessment, the semi structured interview questions used for the exit interviews were also completed, described in Chapter 6 under (outcome assessment) section. Apart from the exit interviews, all final assessments were performed by an external assessor.

7.2.5 Statistical plan

As this was a feasibility study, a prospective sample size calculation was not required (594,699,731). The aim was to recruit a minimum of 6 stroke survivor participants as a convenient sample, initially more participants will be screened and enrolled to ensure meeting the target number of participants.

Acceptability was determined by thematic analysis from the exit interview, and the secondary usability scales, where percentages and mode (i.e., the most frequent) scores among participants. The adherence to exercise through the 8-week HOLOBalance exercise program was assessed from the HOLOBalance system by attendance and completion of the programme. The adherence to home exercise program was assessed from the exercise log. For the secondary outcomes, no statistical analyses were performed due to the small sample size, and the variables were not normally distributed. Percentage change in pre-post intervention scores were reported.

7.3 Results

7.3.1 Participants

Ten stroke survivors who showed their interest in participating in the study from the community centre and stroke association were assessed for eligibility. Two stroke survivors declined to participate due to difficulty in commuting to a 10-week programme. Eight stroke survivors agreed to participate in this feasibility study. The study was conducted during the COVID-19 pandemic, during which stroke survivors were classified as a "vulnerable" group and thus only a limited number of participants were recruited. The CONSORT diagram presents the participants' flow through the study (Figure 7-1).

Participants' mean ± standard deviation age was 63 ±7; 6 were female and 2 were male, all participants had experienced a stroke more than 6 months ago (range 1 - 14 years ago). Six participants had left-sided and 2 had right-sided hemiparesis. Age, weight, and height data are presented in Table 7-1.

7.3.2 Safety

No adverse events were recorded relating to the study. One participant dropped out due to sustaining an injury following a fall at home in the morning after having breakfast during week 5 of the rehabilitation programme. His fall was not related to the HOLOBalance programme.

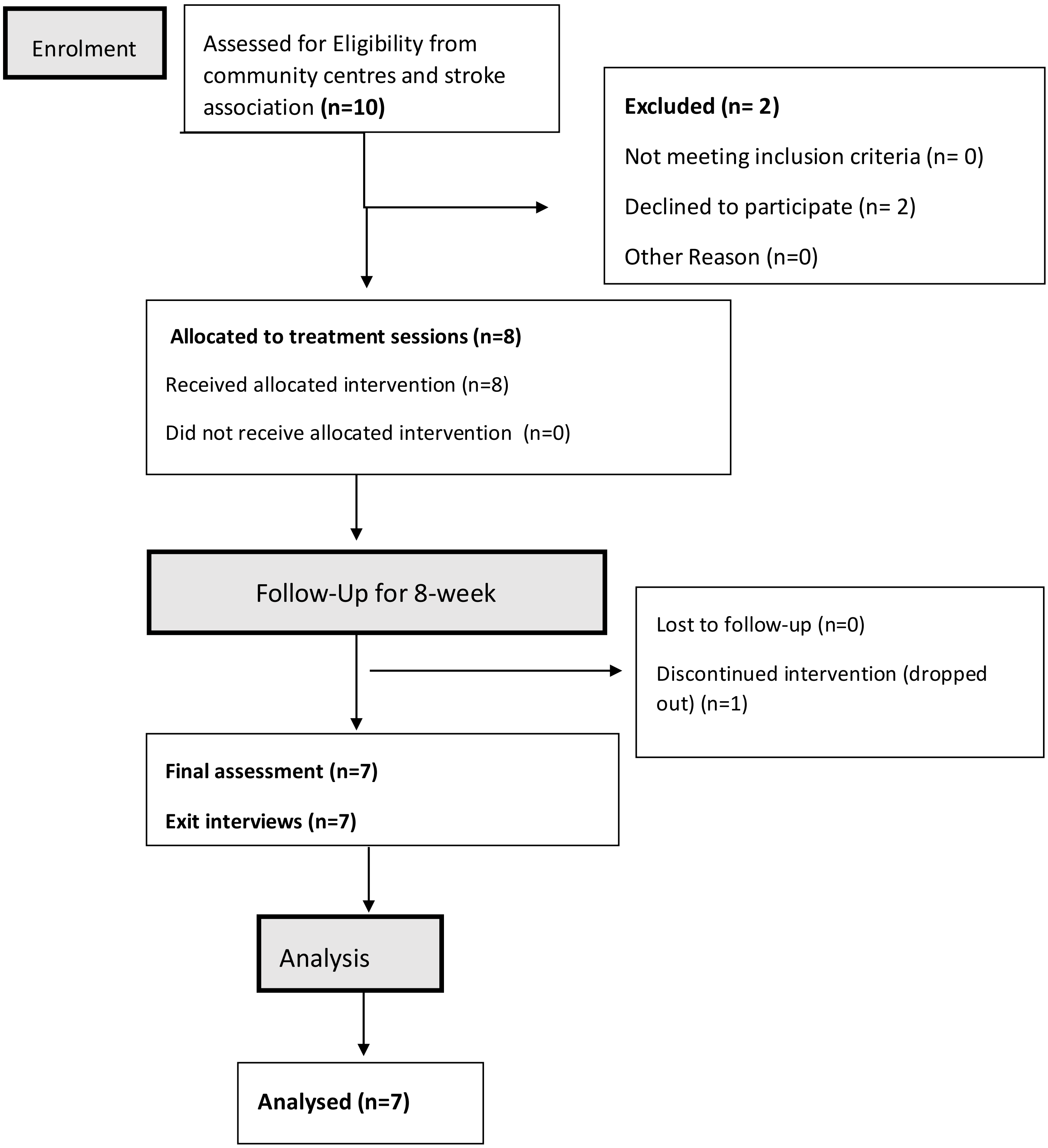


Figure 7—1 The CONSORT diagram for the HOLOBALANCE feasibility study for stroke survivors.

Participant ID	**Age**	**Stroke onset**	**Hemiparesis side**	**Height (cm.)**	**Weight (Kg.)**
H1	58	2009	Left	163	49
H2	73	2015	Left	166	70
H3	71	2008	Left	165	65
H4	71	2012	Left	165.5	95
H5	68	2021	Left	165	98
H6	65	2015	Right	152	65
H7	55	2020	Left	179	80
H8	62	2020	Right	165.5	90
Mean ±SD	63 ±7			165 ±7	76 ±17

Table 7-1 Demographic data for each stroke participant.

7.3.3 Feasibility

The recruitment rate was 80% for eligible participants, with 8 out of a total of 10 volunteers being eligible. These participants subsequently proceeded to enrolled in the study after the screening process was completed. Feasibility and usability data are described below.

7.3.3.1 System Usability Scale

Three participants rated the programme ≥ 75% indicating excellent usability, while the other four participants who completed the programme rated it >50%, indicating good usability. A histogram illustrating individual System Usability Scores is included below (Figure 7-2).

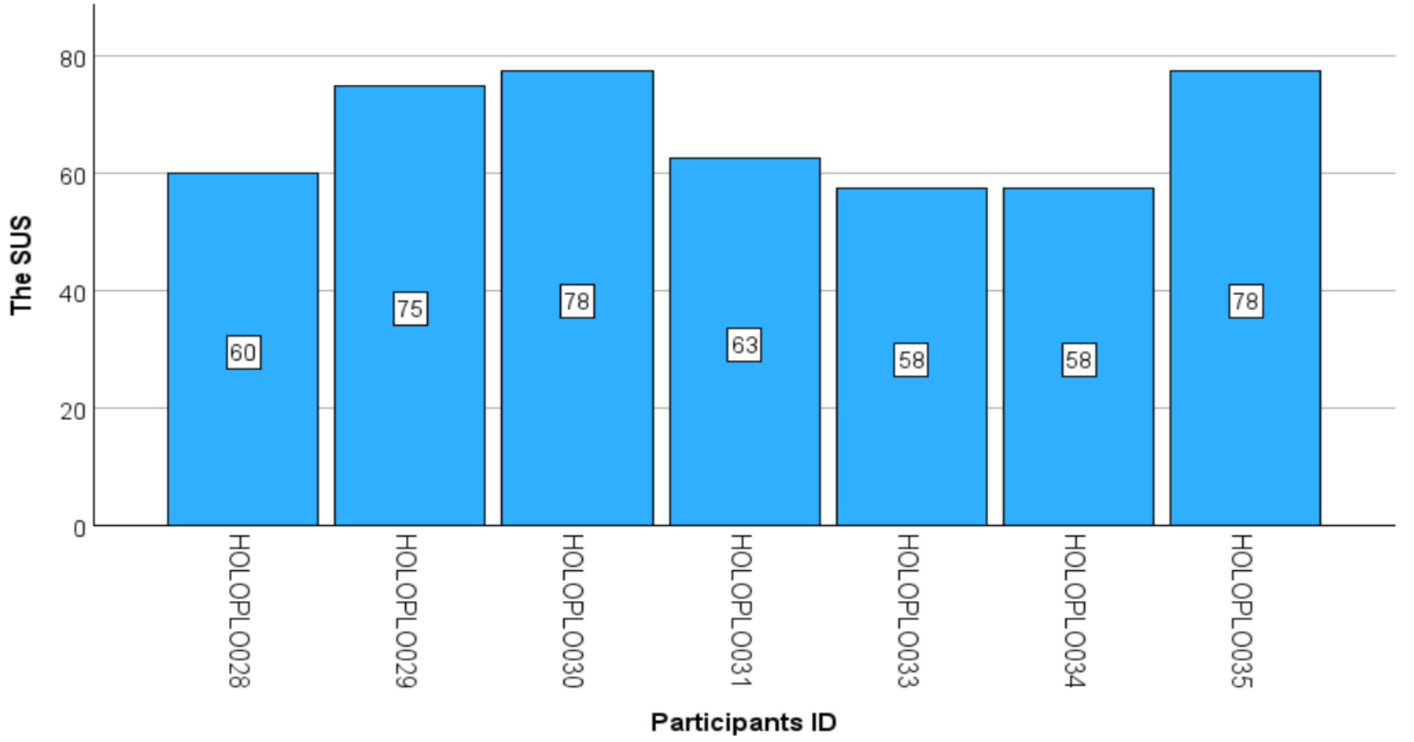


Figure 7—2 Histogram for the System Usability Scale (SUS) scores as rated by each stroke survivor's participant (ranged from 58 to 78).

7.3.3.2 User Experience Questionnaire

Table 7-2 presents the mode (highest frequency) for the User Experience Questionnaire items (-3 represents the most negative response to 3 the most positive response). Five participants reported that the HOLOBalance system was enjoyable, understandable, and clear. For efficiency, 6 participants reported that it was slow; for dependability, 4 participants reported as being supportive; and 3 participants reported as being valuable, creative, and innovative.

	The UEQ items	Mode (highest frequency)
Attractiveness	annoying - enjoyable	2
	good - bad	-2
	unlikable - pleasing	-2
	unpleasant - pleasant	-2
	attractive - unattractive	0
	friendly - unfriendly	-1
Perspicuity	not understandable - understandable	3
	easy to learn - difficult to learn	0
	complicated - easy	0
	clear - confusing	1
Efficiency	fast / slow	-1
	inefficient - efficient	-2
	impractical - practical	0
	organized - cluttered	-1
Dependability	unpredictable - predictable	1
	obstructive - supportive	2
	secure - not secure	1
	meets expectations - does not meet expectations	2
Stimulation	valuable - inferior	2
	boring - exiting	1
	not interesting - interesting	-1
	motivating - demotivating	-1
Novelty	creative - dull	2
	inventive - conventional	3
	usual - leading edge	2
	conservative - innovative	2

Table 7-2 The mode (highest frequency) for the User Experience Questionnaire (UEQ) items (-3 represents the most negative response to 3 the most positive response).

7.3.3.3 The Nasa Task Load Index

No task load reached above 16 (out of 21) in all participants for the mental, physical, and temporal demand, and ranged from 2-15, 3-12, 1-10, and 2-16 respectively. Also, performance, effort demand and frustration demonstrated similar scores, ranging 3-16, 2-14, and 2-16 respectively. Participants scores are presented in Table 7-3.

Participant	Mental demand	Physical demand	Temporal demand	Performance demand	Effort demand	Frustration
H1	15	4	10	16	10	16
H2	2	6	1	7	2	2
H3	4	6	3	3	11	9
H4	6	3	8	4	3	8
H5	7	12	10	8	14	10
H6	12	12	10	14	14	3
H7	5	5	7	7	7	3

Table 7-3 The NASA task load index scores rated by each participant.

7.3.4 Acceptability

Seven participants completed the exit interviews. The interviews identified that the reasons were to improve balance and increase physical activity. By the end of the treatment sessions, participants noticed that their balance had improved; they reported less fear of falling and lower frequency of falls. Additionally, one participant reported that they are “more confident in walking in the community and walking up and down the stairs without holding the handrail”. The favourite exercises and games were standing on the foam cushion, walking with head turns, as well as catching the apples and card memory cognitive games. In addition, standing on the foam, the dog jumping in and reaching up, cognitive games and walking with head turns, were the exercises that participants felt helped improve their balance the most.

One participant acknowledged the improvement she had achieved and commented that "after I joined the programme, I was able to use the train and travel to Nottingham alone, for first time since I had the stroke".

Problems or frustrations with the exercises and games were related to the difficulty in wearing the sensors especially if a stroke survivor had severe upper limb impairment and when needing to insert the insole for participants who wear an ankle-foot orthosis. The commands from the system to “tap the feet” frequently, which occurred when the insole connection to the system was poor, were frustrating. The least favourite part of the HOLOBalance system was the Head-Mounted Device as they reported its weight was heavy; the most interesting part was the creativity and clarity of the hologram presentation and delivery of exercise instructions.

7.3.5 Adherence to exercise

In the treatment sessions: The adherence to exercise in the treatment sessions was identified from the HOLOBalance platform (https://portals.rrdweb.nl/holobalance/index.php). Seven participants completed the HOLOBalance programme, 5 participants completed 8-week treatment sessions, 2 participants completed 6 weeks and had cancelled 4 sessions due to personal reasons. Only one participant dropped out after completing 5 weeks of the program because he had a fall at home which caused a rib fracture (and was reported as an unrelated adverse event).

Home exercises: The exercise log data showed that all participants managed to follow the home exercise programme, however one participant had difficulties because she was unable to follow all exercises without supervision, therefore, the home exercises only included ones in sitting. Exercise progression was dependent on a participant's capability in performing the exercises and the researcher's clinical reasoning. For example, progression to walk while turning the head in V shape was reached after successfully performing walking with head (right/left) turns. All participants were able to progress their exercises every 2 - 3 weeks.

7.3.6 Physical assessment

The pre, post and percentage change in scores of both Mini-BESTest and FGA are presented in Table 7-4. The percentage change in scores for Mini-BESTest and FGA indicating increased (i.e., improvement) in postintervention, ranged from 14% to 32%, and 13% to 27% respectively. More than 15% score change improvements were observed in 4 participants for the Mini-BESTest, and 5 participants for the FGA. Figures 7-3 and 7-4 illustrate the improvement in Mini-BESTest and FGA for each participant, respectively.

Participant ID	**Mini-BESTest**			**FGA**		
	Pre	Post	%change	Pre	Post	%change
H1	22	26	18%	22	27	23%
H2	26	26	0%	24	28	18%
H3	19	20	4%	20	23	13%
H4	20	24	18%	19	24	23%
H5	10	13	14%	9	14	22%
H6	15	22	32%	11	17	27%
H7	14	18	18%	13	16	13%

Table 7-4 Mini-Balance Evaluation Test (Mini-BESTest) and Functional Gait Assessment (FGA) pre and post intervention for each participant.

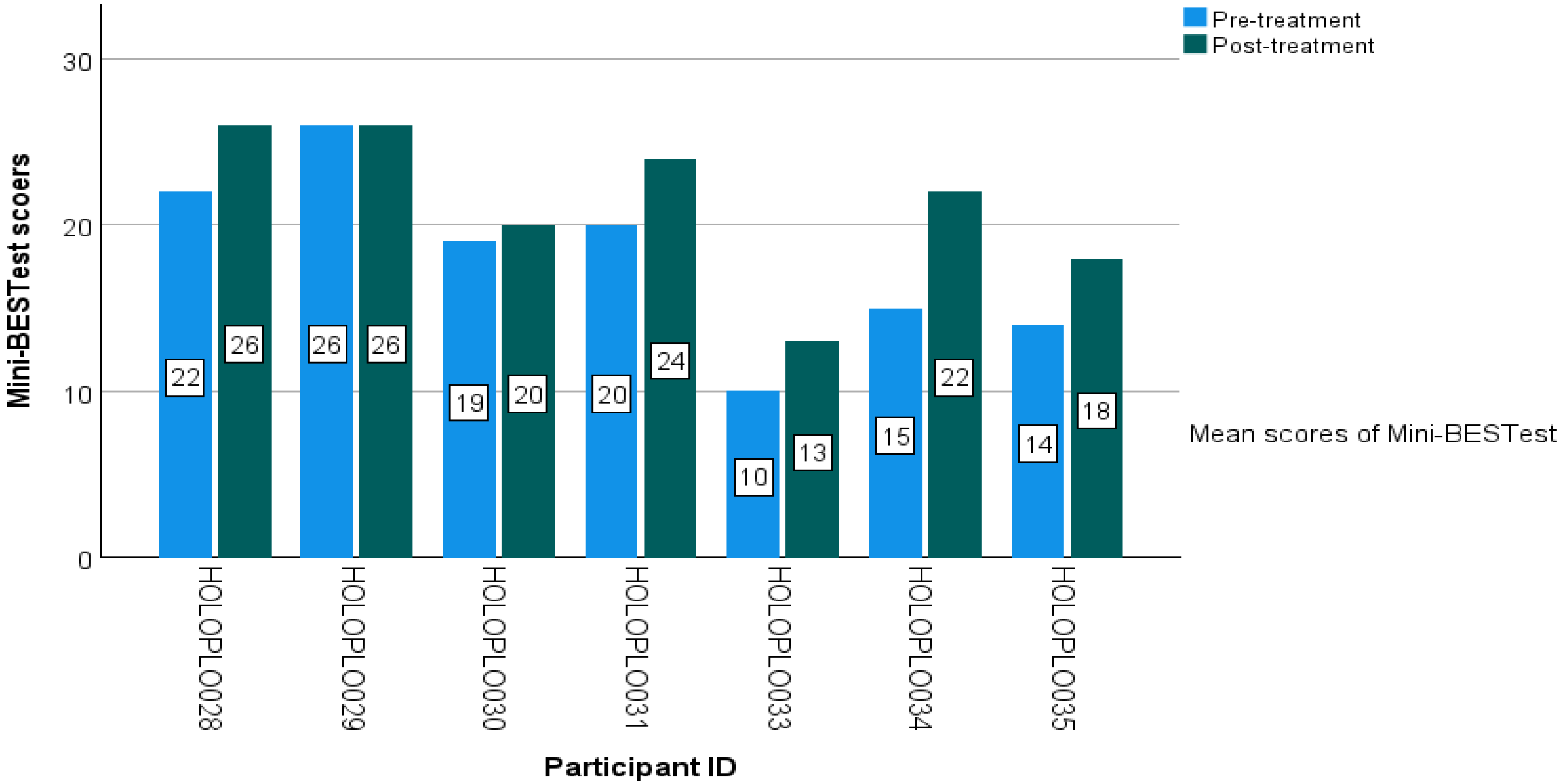


Figure 7—3 Mini-Balance Evaluation System Test (Mini-BESTest) pre- and postintervention for each stroke participant.

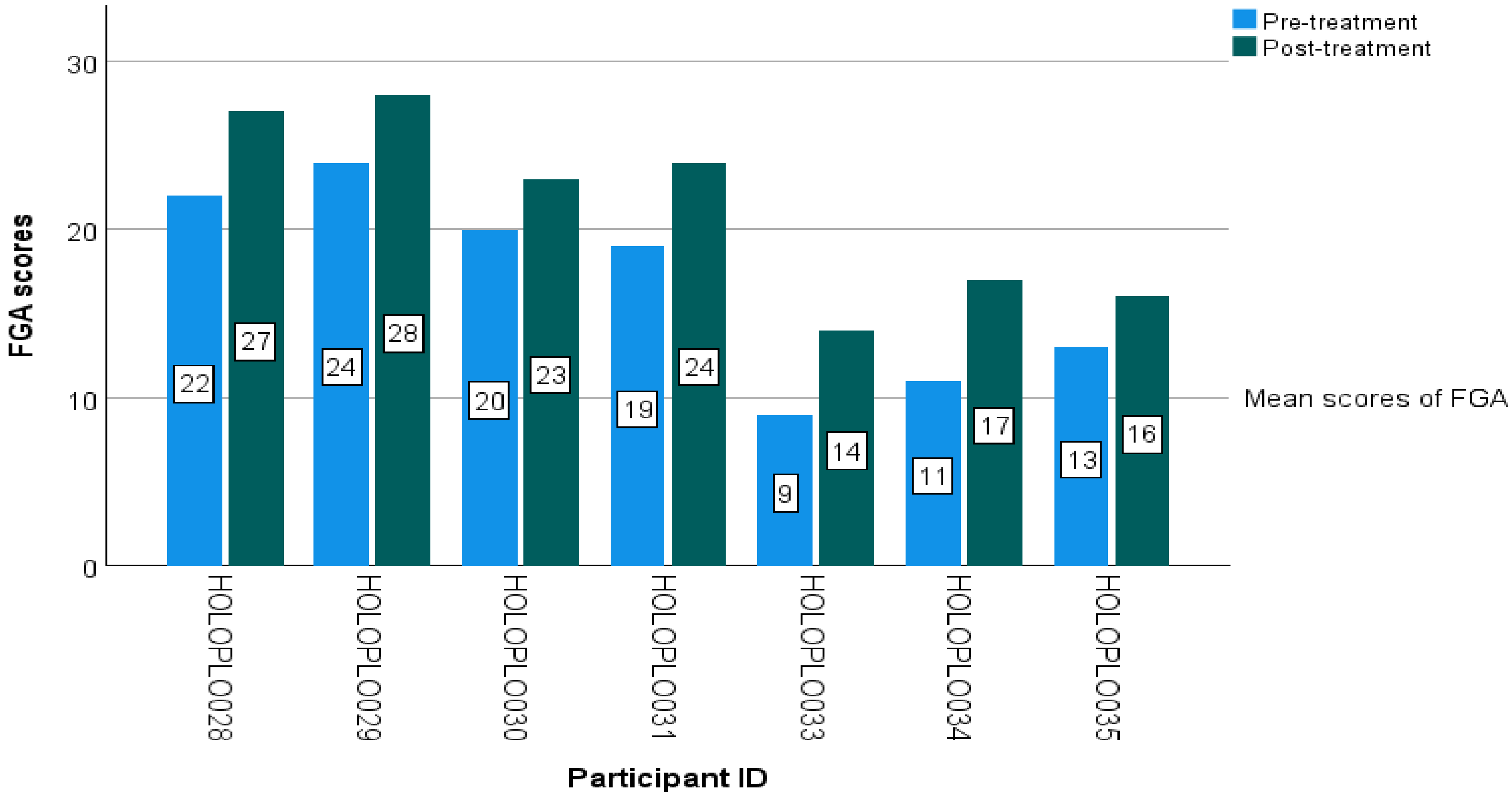


Figure 7—4 Functional Gait Assessment (FGA) pre- and post-intervention for each stroke participant.

7.3.7 Cognitive assessment

Table 7-5 presents participants CANTAB scores. The % change in pre-post treatment scores indicate decreased (i.e., better scores) latency time in seconds (>15%) for 4 tests as follows: four participants in the motor screening task, 6 participants in Multitasking test, 3 participants in reaction time task, and 5 participants in rapid visual information process task. In the paired associated learning task one participant was able to perform the test with no incorrect choice in post-intervention assessment.

Participant ID	MOT			MTS			PAL			RTI			RVP		
	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change
H1	922	853	7% decrease	2640	2405	8% decrease	2	5	150% increase	381	382	0.24% increase	556	535	4% decrease
H2	963	937	3% decrease	3951	2421	38% decrease	13	10	23% decrease	467	456	2% decrease	644	660	2% increase
H3	793	839	5% increase	3958	3941	0.5% decrease	12	24	100% increase	443	438	1% decrease	470	438	6% decrease
H4	1046	2083	99% increase	5699	5633	1% decrease	64	61	5% decrease	415	420	1% decrease	548	548	0%
H5	1249	768	38% decrease	6789	4022	40% decrease	15	40	166% increase	556	646	16% increase	891	678	24% decrease
H6	849	995	17% increase	3469	4030	16% increase	2	0	100% decrease	478	524	9% increase	672	751	11% decrease
H7	1750	1072	39% decrease	6800	5802	15% decrease	63	57	9% decrease	605	643	6% increase	539	456	15% decrease

Table 7-5 The % change in score for each participant in the Motor screening task (MOT), Match to sample visual search (MTS), and Paired associates learning (PAL) tests, Reaction time task, (RTI), Rapid visual information process (RVP) tests. Scores presented are the latency time in seconds for MOT, MTS, and in PAL, the score is from the number of times the subject chose incorrect box.

7.3.8 Subjective assessment for psychosocial aspects

Pre- and post- intervention scores and percentage change for all self-rated questionnaires are demonstrated in Tables 7-6 and 7-7. In the Physical Activity Scale for Individuals with Physical Disability improvement (i.e., increases) ranged from 2% to 70%, and one participant had no change in post-intervention score. For the Activities-specific Balance Confidence scale, improvement (i.e., increased) scores ranged from 39% to 125%, but 3 cases show no pre-post treatment change. The improvement (i.e., decreased scores) for WHO- disability assessment schedule ranged from 6% to 90%, except for one participant had no change.

Trends of better scores were also observed for the Falls Efficacy Scale International (i.e., decreased scores), and Health-related Quality of Life questionnaire (i.e., increased scores) for all participants except one participant in each.

Better scores in the Environmental Analysis of Mobility Questionnaire, in the encounter section (i.e., increased scores) in 3 participants and in the avoidance section (i.e., decreased scores) in 4 participants, but no change in other participants. For the Behaviour regulation in exercise questionnaire an improvement was noted for all participants, except one.

In the hospital and anxiety scale, improvement (i.e., decreased scores) was noted in 4 participants, ranging from 9% to 50% in the anxiety section, and in 3 participants, ranging from 4% to 27% in the depression section. Other participants had no increased symptoms (normal scores) in pre- intervention and no change post- intervention. Similarly, for dizziness handicap inventory, two participants showed improvement (i.e., decreased scores) post-intervention, other participants had no dizziness in pre-intervention.

Participant ID	PASIPD			WHODAS			ABC scale			FES-I			EQ-5D-5L		
	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change
H1	214	300	10% decrease	37	27	27% decrease	32	70	115% increase	36	23	36% decrease	65	75	15% increase
H2	212	352	66% increase	4	2	50% decrease	83	96	96% increase	26	18	30% decrease	80	90	12% increase
H3	246	251	2% increase	10	8	20% decrease	73	73	0%	28	28	0%	90	97	7% increase
H4	250	335	32% increase	10	4	90% decrease	64	89	39% increase	22	21	4% decrease	80	90	12% increase
H5	423	423	0%	35	35	0%	21	21	0%	37	36	2% decrease	60	60	0%
H6	160	200	25% increase	48	45	6% decrease	20	45	125%	47	45	4% decrease	75	85	13% increase
H7	235	400	70% increase	37	17	54% decrease	79	79	0%	34	20	41% decrease	70	80	14% increase

Table 7-6 The individual scores for pre- and post- intervention and the percentage (%) change in scores in each participant for the Physical Activity Scale for Individuals with Physical Disability (PASIPD), the World Health Organisation Disability Assessment Schedule (WHODAS), Activities-specific Balance Confidence (ABC) scale, the Falls Efficacy Scale International (FES-I), and the Health-related Quality of Life (EQ-5D-5L) questionnaire.

Participant ID	EAMQ (Encounter)			EAMQ (Avoidance)			BREQ			HAD (anxiety)			HAD (depression)			DHI		
	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change	Pre	Post	%change
H1	1	2	100% increase	2	2	0%	58	62	6% increase	10	6	18% decrease	11	5	27% decrease	30	25	16% decrease
H2	2	2	0%	1	1	0%	19	18	5% decrease	9	7	9% decrease	7	6	4% decrease	0	0	0%
H3	2	2	0%	2	1	50% decrease	53	66	24% increase	0	0	0%	1	1	0%	0	0	0%
H4	2	3	50% increase	1	0	50% decrease	48	68	41% increase	15	10	33% decrease	13	7	27% decrease	0	0	0%
H5	2	2	0%	3	2	33% decrease	11	12	9% increase	10	10	0%	12	12	0%	20	20	0%
H6	1	2	100% increase	3	1	66% decrease	33	60	81% increase	8	6	9% decrease	6	6	0%	84	30	37% decrease
H7	2	2	0%	2	2	0%	40	44	10% increase	1	1	0%	1	1	0%	0	0	0%

Table 7-7 The individual scores for pre- and post- intervention and the percentage (%) change in scores in each participant for the Environmental Analysis of Mobility Questionnaire (EAMQ) (Encounter and Avoidance), the Behaviour regulation in exercise questionnaire (BREQ-3), the Hospital Anxiety and Depression scale (HAD depression, HAD anxiety) and Dizziness Handicap Inventory (DHI).

7.4 Discussion

This study aimed to assess the acceptability and feasibility of the HOLOBalance system to deliver balance training for stroke survivors. The HOLOBalance programme was deemed safe, and no adverse events were reported. Although the main aim of HOLOBalance system was for balance training at home, this was initially performed in a laboratory university setting for safety reasons. The feasibility, acceptability, and trends of improvement in the physical, cognitive, and psychosocial aspects are discussed below.

7.4.1 Feasibility and acceptability of the HOLOBalance (Clinic- based) system

The exit interviews showed that participants found the HOLOBalance system acceptable and feasible and noticed improvement in specific daily activities such as climbing stairs and walking in the community. The usability of the HOLOBalance system was good. The system uses a hologram, and the exercises presented with AR, which helps increase motivation and provides feedback on participants' performance. Additionally, for cognitive exergames, participants were able to undertake exercises in an engaging environment. One of the benefits of feasibility studies is to identify suitable users (700,715). In this study, participants had an average age of 63 years, the stroke onset ranged from one to 14 years, and were able to walk independently with or without a cane. The treatment sessions were under supervision for all participants, and participants with moderate or severe upper limb paralysis required more time and help putting on wearable devices.

Current results are similar to those reported in previous AR studies specifically focused on activity training (373,732). The User Experience Questionnaire reveals that the system was enjoyable, understandable, and innovative but slow. Rehabilitation provision via AR systems might be associated with some frustration since the use of AR is still in its early stages in this area (373). Although frustration associated with the use of technology is common in healthcare (733), in the HOLOBalance system, participants reported low frustration levels. In the NASA TLX load, there were no high scores recorded in all subitems, including the "demand load".

In contrast, stroke survivors reported some difficulties and required help and more time, for example, wearing the insole sensors and head-mounted device due to the limitations in upper limb functioning (734). Technical difficulty is one of the main factors influencing the usability of telerehabilitation in chronic stroke survivors, as identified in a recent systematic review which included 31 studies for synchronous and asynchronous telerehabilitation and tele-support (166). Technical difficulties would increase the level of frustration, which might be lowered by adding an introductory practical workshop for participants before starting the treatment programme to assess the required level of help in handling the equipment. This is in line with previous studies demonstrating that handling the devices can be difficult for people with neurological conditions (735,736).

7.4.2 Adherence to exercise

Adherence to exercise from the HOLOBalance system was high for the entire duration of the study. Telerehabilitation has been shown to increase adherence rate (341,361,376), and a previous systematic review on the feasibility of telerehabilitation and virtual reality-based balance training for stroke survivors by Schröder et al (2019) showed that adherence rates were good and helped participants continue with the exercises after discharge from rehabilitation centres since it increased enjoyment and motivation (737). However, the length of adherence was not measured in the Schröder et al's review. The adherence needs to be assessed not only if patients follow with the exercise but also the intensity of the exercise needs to be assessed in future studies.

One potential remedy is to tailor programs, as it was found that adherence to the home exercise programme which was prescribed according to individual capacity to follow the treatment session exercises, was good. Home programmes can encourage patients' self-management for the rehabilitation process (697), and help improve balance and functional gait outcomes. In the current study, 2 participants were at high risk of falls, had a history of fractures, and were not confident in performing all exercises as performed in the treatment sessions; thus, home exercises were limited to exercise from sitting position. For safety purposes, home exercises should be performed in high precautions with no challenges in doing the exercises. This agrees with a recent clinical trial by Lee et al (2023) which found that stroke home exercise programmes need more safety precautions when participants have a fear of falling and they are at high risk of falls (738).

7.4.3 Balance and functional gait

All participants demonstrated trends of improvement in balance and functional gait in the final assessment. The customised MSR exercises were prescribed and progressed according to each participant's ability. Four participants in the Mini-BESTest, and five participants in the FGA had an improvement above 15% (4.5 points) which is above the minimum detectable change for both measures. These are in line with previous studies on the effect of MSR exercises in improving balance and gait after stroke and enhancing proprioception, sensory motor integration and vestibular function (48,689,716,739). These very early findings are in line with previous studies which showed that telerehabilitation can help to improve physical functioning, activities of daily living and health-related quality of life (67,69).

Furthermore, adding virtual reality and gaming exercises in rehabilitation has been shown to help increase physical function (740), balance (741–743), walking speed and motivation (744). In addition to the HOLOBalance programme in the clinic, participants were committed to the individually prescribed MSR exercises as a home programme on days with no clinical sessions. Home exercise helps in maintaining motor recovery level (745), can reduce sedentary behaviour (746) and increase daily activity (747).

In participants that did not achieve a 15% change, this may be due to the difficulty experienced when performing certain tasks in the Mini-BESTest and FGA assessments. The addition of specific types of exercises with more repetitions may be helpful for stroke survivors with moderate lower limb paresis since muscle strength and thickness are affected on the bilateral side (748). Adding resistance exercises (749,750) for longer durations (751) is recommended for stroke survivors with moderate to low paresis in addition to MSR exercises.

7.4.4 Cognitive tasks and exergames

In the current study, exergames showed a trend of improvement in cognitive functions, which aligns with findings for patients with other neurological conditions (752). All CANTAB tests (motor screening, multitasking, rapid visual information process and paired associated learning tasks) showed better scores in post-intervention in 4 of the participants, except in the reaction time task where the improvement was lower. Egerhazi et al (513) highlighted that people with mild cognitive impairment have significant decline in the reaction time task compared to healthy controls, since the task is designed to measure the speed of response to a visual target where the stimulus is either predictable (one circle) or unpredictable (multiple circles) (513). Stroke survivors have a decline in sustained, selective attention, and motor accuracy (753–755), all of which are required for the reaction time task. No previous studies on cognitive training for stroke with mild cognitive impairment have been found. However, a literature review showed that cognitive rehabilitation improves stroke survivors' performance in daily living activities (756), although no details on the type of cognitive assessment used were provided. Preliminary data from a randomised controlled study of stroke survivors showed that the group who received cognitive task training had a significant improvement in the TUG test and BBS after DT intervention compared to the single motor task group; however, no cognitive tests were used to assess the cognitive function (757).

7.4.5 Psychosocial aspects

Preliminary data showed better scores in postintervention in the following self-reported questionnaires for physical activity, WHO disability assessment, balance confidence, quality of life, environmental analysis of mobility, behavioural regulation in exercise, and falls efficacy. Potential improvement in subjective symptoms and level of social participation can help in minimising the consequences of physical disability from stroke, increasing participant balance confidence, and potentially reducing falls (46,250,519). This is in concurrence with the findings from the participant exit interview in the current study, as one participant commented she was "able to travel alone using a train since she had the stroke".

Furthermore, in the current study, the percentage change in post-intervention score indicated improvement among participants who had increased symptoms of depression, anxiety, or dizziness. MSR exercises help decrease dizziness symptoms by, stimulating sensory input (vestibular, visual, and proprioceptive), which is required for anticipatory postural changes and adjustments to environmental challenges such as changing surfaces for balance maintenance (41,168).

7.4.6 The feasibility of the HOLOBalance system for balance training for older adults at risk of falls and stroke survivors

Balance training using the HOLOBalance system for stroke survivors was feasible and acceptable according to the exit interviews and the usability and acceptability scales, which is in line with the results from older adults at risk of falls reported in Chapter 6. The exit interviews revealed that older adults at risk of falls and stroke survivors noted that their balance improved after completion of the HOLOBalance/HOLOBox programme with MSR exercises, cognitive and auditory tasks. Furthermore, the exergames and cognitive training were reported to be enjoyable. The feasibility of using the system for older adults at risk of falls was studied in both laboratory and home-based environments and compared to the control group. However, for stroke survivors, the feasibility study was limited to the laboratory environment with no control group because of limited time and difficulty in recruiting stroke survivors. Further studies for The use of the HOLOBalance (home-based) system are important since stroke survivors would be able to perform individualised exercises at their convenience, with all exercises being followed and monitored by a physiotherapist (376).

7.4.7 Limitations of the study

Only a small number of participants were recruited due to difficulty of recruitment during the COVID-19 pandemic and the timeframe.

In addition, the findings are limited to those who fit the inclusion criteria, who had no or mild cognitive impairment, were able to walk 6 metres independently, and the participants' average age was 63 which limits the generalisability and the feasibility for stroke survivors with different levels of impairments. Additionally, the feasibility of the system was tested in a controlled laboratory environment and under supervision; further studies are needed to assess feasibility in a home environment.

The balance and gait assessments were based on clinical tests and performance observation; and more objective assessments are needed. Adherence to home exercises needs to be measured with more specificity. Other limitations include the inability to have a control group, and a lack of follow-up assessment after the intervention period. In addition, the initial assessment and the exit interviews not being performed by an external assessor, which reduced external validity.

7.4.8 Recommendations for future studies

Further studies with larger sample sizes are recommended, in addition to including stroke survivors with different levels of impairment. It is suggested that, for stroke survivors with upper limb paresis or those who need ankle-foot orthosis while walking, the system could be adapted to have fewer wearable sensors.

Other exercises for muscle strengthening and aerobic exercises in addition to the MSR and cognitive training can be implemented to enhance motor recovery. In the pre- and post-treatment assessment, in addition to using more objective tests for balance and gait, DT walking tests could be used to identify the motor-cognitive interference pre- and post-intervention and avoid the ceiling effect in other balance measurements.

Future studies are needed to assess the feasibility of the system for home users, since this will allow stroke survivors to perform individualised exercises at their convenience in their home, and which can be followed and monitored by a physiotherapist.

7.4.9 Implications for clinical practice

This study demonstrates the feasibility of using the HOLOBalance system to deliver balance training for stroke survivors, indicating a few informative points for stroke balance rehabilitation practice. The use of telerehabilitation provides more enjoyment and helps in increasing adherence rates. Chronic stroke survivors able to walk 6 metres independently and who have no, or mild, cognitive impairment need individualised balance rehabilitation to target their specific needs. Moreover, balance rehabilitation with the MSR exercises to stimulate the vestibular system (329), in addition to the cognitive training (608) can be added to the traditional balance exercises for ambulatory chronic stroke survivors.

Furthermore, the goals of rehabilitation can be recorded in the system in addition to the exercise performance allowing for more effective communication between health practitioners (376).

7.4.10 Conclusion

In conclusion, the findings of this study indicate that balance training with the HOLOBalance system in clinic (HOLOBox) was feasible and acceptable for stroke survivors. There was potential improvement in clinical outcomes for balance and functional gait as well as for certain cognitive function tasks. Additionally, the fear of falling was reduced after the intervention. Further studies are needed to investigate the feasibility and acceptability of the HOLOBalance system at home for stroke rehabilitation and to compare the cost and clinical efficacy of the HOLOBalance system compared to balance and cognitive exercises provided without a telerehabilitation solution.

Chapter 8: General Discussion

This chapter will provide a summary of each study's aims and results presented in this thesis, in addition to providing a general discussion, and outlining the limitations. This will be followed by the implications of the main findings and overall conclusions.

8.1 Context of the project

Stroke incidence and prevalence have been increasing globally over the last few years according to the Global Burden of Diseases, Injuries, and Risk Factors Study from 1990 to 2019 (20). In addition, Feigin et al (2022) indicated in the global stroke fact sheet that stroke remains the second-leading cause of death and the third-leading cause of death and disability combined globally (758). Moderate to severe mobility problems are present in more than 1/3 of stroke cases (592). Although the majority of stroke survivors (85%) are able to walk, only around 45% are able to regain function for day-to-day activities (57). The assessment and treatment of dynamic balance and functional gait are not addressed robustly in traditional rehabilitation programmes for stroke survivors and are usually limited to performing sit-to-stand tasks and/or simple walking exercises (36).

However, balance is a multifactorial process and requires the integration of sensory inputs (somatosensory, visual, and vestibular systems), and musculoskeletal components (40,759). Furthermore, the performance of daily living tasks, such as crossing the road, requires the regulation and integration of cognitive function, mainly working memory, attention, and executive function (616). In addition to physical capacity, and cognitive function, balance and functional walking can also be associated with other factors such as psychological status

(590). Therefore, the assessment and treatment of stroke survivors should include all components of balance and functional walking and factors that may impact on outcomes.

In addition, adherence rates for practise of home exercises are currently reported to be low in stroke survivors (660). A systematic review by Hawley-Hague et al (2022) has shown that the provision of physiotherapy exercises delivered remotely for people with neurological conditions helps to increase the accessibility and adherence rate to intervention programmes (760). Therefore, providing individualised exercise training that covers all balance components via a telerehabilitation system may help to improve adherence to exercise, which would contribute to improved rehabilitation outcomes.

The overall aims of the studies presented in this thesis were to

1) Identify the optimal Outcome Measures (OM) based on psychometric properties for assessing walking at a functional level which includes dynamic balance, functional walking and dual task (DT) walking.

2) Identify the factors associated with walking at a functional level in ambulatory chronic stroke survivors in comparisons to healthy controls.

3) Determine the feasibility and acceptability of a novel telerehabilitation (HOLOBalance) system for older adults at risk of falls and ambulatory chronic stroke survivors.

8.2 Assessment of walking at a functional level for stroke survivors

The use of spatiotemporal tests, such as the 10-metre walk test, which assess walking speed only, is insufficient for assessing community walking for stroke survivors (479). Performing a functional activity while walking such as crossing the road requires more than sufficient gait speed in isolation, but also the ability to be able to perform complex movements, such as turning the head whilst walking (57). Furthermore, the ability to perform a simultaneous cognitive task is also a requirement for walking safely in the community (55,305).

A systematic review was conducted (Chapter 3) to identify the OMs used to assess walking at a functional level for ambulatory stroke survivors. These measures include the assessment of dynamic balance, functional, and DT walking. The psychometric properties of these assessments were appraised based on the COSMIN risk of bias assessment tool for good measurement (411). The review included 54 studies (30 OM) for dynamic balance, functional and DT while walking used in stroke rehabilitation. Reliability was the most tested property followed by validity, however, data on responsiveness was limited. Further studies are needed to evaluate other important measurement characteristics such as interpretability and minimum detectable change.

According to the COSMIN tool, the best psychometric properties were reported for the BESTest and Mini-BESTest in the dynamic balance category and the DGI and FGA for functional gait. To assess more challenging dynamic balance and walking ability it is recommended that there should be an assessment of DT while walking, for example performing a cognitive function task, such as verbal fluency or mental arithmetic, whilst simultaneously walking.

Difficulty of cognitive DT varies according to the secondary task chosen, for example for verbal fluency, saying alternate letters of the alphabet, or remembering a shopping list (480).

Among the studies included in the systematic review, the most widely tested validity was the construct validity which assesses the correlation between OM. However, there is a need to investigate structural validity, which tests the dimensionality of an instrument, in order to evaluate the required aspects of measurement. Most of the OM used to assess walking at a functional level in previous studies included tasks used for people with limited function in balance and gait in general but not specific for stroke survivors' requirements. For example, although stroke survivors can have multiple forms of sensory neglect, affecting auditory, olfactory, or tactile sensation, visuospatial neglect symptoms have the most significant impact on neurorehabilitation and activity of daily living and studies on how visuospatial neglect can affect functional activity are limited (761). A previous review by Embrechts et al (2021) included 48 studies and identified that there was an association between visuospatial neglect and balance control more in the mediolateral than the anterior-posterior directions (762) which reflects increased difficulty in balance control in mediolateral direction.

The assessment of visuospatial perception is challenging for many reasons, such as the requirement of a drawing response and the lack of sensitivity (763–765). The common test of visual spatial neglect is the star test, which can determine the presence but not the absence of visual spatial deficits (766). The test can vary according to situation, for instance sitting in a clinic versus walking on a busy street. It is suggested for future studies to add visuospatial attention tests such as the star test while performing assessment of dynamic balance and functional walking as these might help in determining the limitation in visuospatial attention at the functional level.

Moreover, studies have shown that deficits in visuospatial attention and executive function are common in people who have experienced falls, therefore a comprehensive cognitive function assessment is essential (767,768), even for stroke survivors with no or mild cognitive impairments.

Interestingly, DT conditions were investigated in 36 stroke survivors (mean age 66.5 and SD 11.8, with mean time since stroke onset 16 months) compared to healthy controls. In the DT condition, sway (as measured by a force-measuring plate) was reduced, and gait slowed in both groups ($p < 0.01$ for anterior-posterior sway, stride length, velocity, and walk time). However, in stroke survivors, the increase in walk time was greater (i.e., worse) than in the controls ($F = 4.2$, $p = 0.046$), and cognitive performance deteriorated during the DT gait ($p = 0.017$) (208). This demonstrates the importance of adding the DT while walking to the rehabilitation protocol for stroke survivors.

Additionally, a systematic review of 15 randomized controlled studies by Wang et al (2015) investigated the effect of adding DT training to enhance cognitive-motor interference on gait and balance in stroke survivors (769). The review identified that the DT training group had significant improvements over the other groups (single exercise task or no intervention) in increasing gait speed (mean difference (MD) 0.19 m/s, 95% CI (0.06, 0.31), $P = 0.003$), stride length (MD 12.53 cm, 95% CI (4.07, 20.99), $P = 0.004$), cadence (MD 10.44 steps/min, 95% CI (4.17, 16.71), $P = 0.001$), centre of pressure sway area (MD −1.05, 95% CI (−1.85, −0.26), $P = 0.01$) and Berg Balance Scale (BBS) (MD 2.87, 95% CI (0.54, 5.21), $P = 0.02$) (769). Although the Wang et al (2015) review showed that gait parameters and BBS were improved after the intervention of DT training, the addition of DT walking tests in the assessment would add value as this would assess the level of cognitive-motor interference before/after treatment or between groups and helps in providing more tailored treatment according to patients' level.

Furthermore, a recent protocol by Tasseel-Ponche et al (2023) for a DT walking training program has been published for the sub-acute phase after stroke (770). The protocol comprises various cognitive tasks for executive function, memory, and spatial cognition while walking (770), however, the initial and final assessment did not include the DT while walking assessment which needs to be included for a more valid assessment of the DT intervention.

Overall, it is important to consider OMs in clinical practice and future research which covers challenging tasks for dynamic balance and functional gait, and for more advanced levels, to assess motor-cognitive interferences which can be tested by dual cognitive tasks while walking. The current systematic review was limited to clinical tests based on performance observation. Assessments based on performance are liable to observational bias and need to be interpreted with some caution (771). Ideally, the use of more objective measures such as the Vicon system (560) is recommended in order to provide more comprehensive data on gait analysis.

8.3 Factors associated with walking at a functional level in ambulatory chronic stroke survivors in comparison to healthy controls

The aim of the second study (Chapter 5) was to identify if there is an association between walking at a functional level and a number of factors such as Subjective Visual Verticality (SVV), cognitive functions, psychosocial aspects and physical activity levels in ambulatory chronic stroke survivors compared to healthy controls. Identifying the factors associated with walking at a functional level can help in determining individualised rehabilitation goals for ambulatory chronic stroke survivors to improve their walking in the community (35,592).

The ambulatory chronic stroke survivors in the current study, even though they were able to walk 6 metres independently and had a motor recovery level >43 in Motricity Index, they demonstrated limited walking at a functional level (i.e., low Mini-BESTest and FGA scores) which was significantly lower than healthy controls. Walking at a functional level is a mandatory component for walking safely at the community. A previous review by Moore et al (2022) highlighted that stroke survivors who can walk independently, as assessed clinically, do not necessarily indicate good walking performance in the real world (772). Additionally, studies have shown that, even after mild stroke, survivors ability in recovering walking safely in the community and meet the recommended walking steps (>5000) per day (773).

Walking at a functional level incorporates dynamic balance (Mini-BESTest), functional gait (FGA) and both had a strong association with balance confidence (Activities-specific Balance Confidence Scale) in the stroke survivors' group. This emphasises the importance of adding balance confidence to the assessment and treatment plan for ambulatory stroke survivors. Assessment of balance confidence can be used as a screening tool to help in prioritising treatment goals which aim to optimise walking at a functional level, particularly for stroke survivors who have demonstrated good scores in balance and walking assessment. However, the approaches that can be implemented to help improve balance confidence have not been studied for balance and functional gait in ambulatory stroke survivors yet.

In older adults at risk of falls, both balance confidence and balance ability have been shown to improve after balance training consisting of 30 minutes/2 days a week for 6 weeks (774).

In addition, for older adults at risk of falls, a recent review showed that adding multicomponent behavioural interventions provided the maximum benefit in improving balance confidence and in decreasing activity avoidance compared to traditional exercise training (612). Further studies are required to investigate whether adding behavioural strategies can help to improve balance confidence and therefore improve balance and functional gait for ambulatory stroke survivors.

In the current study, despite the stroke survivors having no increased anxiety and depression levels as assessed by the Hospital Anxiety and Depression Scale (HAD), the Mini-BESTest and the FGA both demonstrated a negative association with the Environmental Analysis Mobility Questionnaire- Avoidance. Assessment of the behavioural changes developed after stroke is important to understand avoidance behaviour. A recent qualitative study by Hall et al (2020) discovered that stroke survivors reported being sedentary, which was related to a decreased confidence in mobility, increased weariness, and poor balance and coordination (775). Further, the Hall et al (2020) study identified that stroke survivors need to be willing to/ and motivated to exercise and to reduce sedentary behaviour (775). It is suggested that stroke survivors who demonstrate high scores in the Environmental Analysis Mobility Questionnaire- Avoidance need to follow an additional screening. The capability, opportunity, and motivation (COM-B) model of behaviour change (776) can be used in future studies to investigate the motivations for engaging in activities and the reasons for avoidance behaviour.

No association was noted between dynamic balance (Mini-BESTest), functional gait (FGA), SVV, cognitive function, depression and anxiety status, or other subjective symptoms in the present study. This may be due to the small sample size, as well as the fact that the scores in the SVV and in the Hospital Anxiety and Depression scale were within normal range for all stroke survivor participants. Previous studies have shown cognitive and psychological factors such as executive functions and depression, respectively, have a negative impact on dynamic balance and functional gait (777). However, in the current study, participants with chronic stroke who had a motor recovery level >43 in the Motricity Index and were capable of independently walking at least 6 metres; no severe anxiety and depression in their psychological status scores. Similarly, their perception of SVV and cognitive function were not significantly affected or improved after stroke. Previous studies have shown that SVV to be associated with balance control in acute stroke (12,93) and in people with vestibular dysfunction with moderate/severe dizziness or vertigo (95,509). Future studies are needed to investigate the association in chronic stroke.

Another potential reason for there being no association between the stated factors and walking at a functional level could be related to the sensitivity and specificity of the assessment. For example, the MoCA test has been suggested for cognitive screening since it has a high sensitivity (ability to identify the presence of an actual deficit, i.e., a true positive result), but the specificity (ability to identify the absence of an actual deficit, i.e., a true negative result) is not high (778,779). Therefore, other tests have been suggested for use in future studies such as Addenbrooke's Cognitive Examination due to its higher specificity and the fact that it includes more tests for visual perception and visuospatial skills (778,780). Further assessment by DT walking test could increase the sensitivity in identifying the challenges in walking at a functional level for ambulatory stroke survivors.

Cognitive dysfunction can result in behavioural changes which might impact walking at a functional level (781,782). However, there are no previous studies on mild cognitive dysfunction in stroke survivors. In patients with Alzheimer's disease, mild cognitive dysfunction was associated with behavioural changes and impacted daily activity (783–785). There are no previous studies on mild cognitive dysfunction in stroke survivors. In patients with Alzheimer's disease, mild cognitive dysfunction was associated with behavioural changes and impact daily activity (783–785). Potentially adding an interview in the assessment battery could help to identify whether stroke survivors with mild cognitive impairment noted behavioural changes after stroke and the impact of mild cognitive dysfunctions on walking at a functional level.

Extensive evaluation of cognitive and psychological aspects after stroke could be enhanced with interdisciplinary teams from occupational therapy and neuropsychology. Moreover, the Royal College of Physicians recommended routine assessment and management of mood and cognition after stroke (786) that will help in preventing depression and deterioration of cognitive dysfunction after stroke (787). In addition, early neuropsychological assessment and management are also required for mild cognitive impairment to improve functional skills (788).

Physical Activity (PA) levels in stroke survivors were also assessed in the second study (Chapter 5). During the 7-day assessment period, stroke survivors demonstrated a high percentage (87%) was recorded as sedentary time. It is suggested that performing adaptive sports can be enjoyable for stroke survivors and help to achieve and maintain a high PA level (789). Adaptive sport is any recreational sport performed by people with motor disabilities that is parallel to typical sports activities, but necessary adaptations have been made. Adaptive sport contributes to maintaining functional autonomy (271). For example, in one cohort study, out-door overground walking (40% of heart rate reserve) had similar results to that of aerobic treadmill training (60-80% of heart rate reserve) when practiced for three 40 min sessions/week over 12 weeks with both groups showing improvements in mobility, endurance, and lower levels of depression (790).

Real-world high PA was not found to be related to time since stroke, nor to age, gender, or social living situation; however, it was strongly associated with balance confidence (55). Previous work has shown that stroke survivors who had a score of > 82/100 on the Activities-specific Balance Confidence scale achieved higher PA (5843 steps/day) than those who had scores of <70/100 (3283 steps/day) (791). Therefore, maintaining high PA levels or improving PA after stroke could be enhanced by improving balance confidence and adding real-world activities to the rehabilitation programme. Further qualitative and longitudinal studies are needed to understand the factors associated with PA for ambulatory stroke survivors.

8.4 The feasibility of the HOLOBalance system for balance training programme

8.4.1 For older adults at risk of falls

Physical distancing during the COVID-19 pandemic made the application of telerehabilitation mandatory for neurorehabilitation (792). Rehabilitation of dynamic balance and functional gait should be targeted toward all factors that contribute to performance, in addition to cognitive function. Rehabilitation programmes cannot focus only on strengthening exercises or a walking programme but should also stimulate sensory input for balance as well as anticipatory postural control, movement strategies, and a structured increase in daily activities. The use of telerehabilitation for rehabilitation has been growing very rapidly in physiotherapy (66,69,71,760). Telerehabilitation with VR was shown in previous studies by Katz et al (2005) and Cano Porras et al (2019) to have a statistically significant effect postintervention for gait (i.e., TUG test), and balance (Mini-BESTest) in patients with different neurological conditions (365,793). Additionally, another study have shown that VR helped in self-management for cognitive skills training (362).

The HOLOBalance system is a new form of telerehabilitation using AR and provides a virtual coach for continuous feedback on safety and exercise performance. The Multi-Sensory Rehabilitation (MSR) exercises, which aimed to activate sensory pathways as well as anticipatory adjustments and movement strategies that contribute to postural control, were implemented together with additional exergames, cognitive games, and auditory tasks (377).

Chapter 6 presents the feasibility study of HOLOBalance for balance training for older adults at risk of falls. Recruitment and adherence rates were good for the HOLOBalance system for the laboratory setting. However, in the home environment, adherence was lower as participants had difficulties in managing the system, despite a leaflet and pictorial guide being provided. The difficulties were particularly related to their ability to handle the equipment, for example charging the batteries required for insole sensors.

In both laboratory and home-based environments, HOLOBalance system was shown to be feasible and acceptable for older adults at risk of falls. This is in agreement with previous studies on telerehabilitation for older adults such as those which looked at the COCARE system (354,355) and the MULTIPLAT_AGE network project (356). Some difficulties relating to technical issues, such as wearing the sensors and maintaining the head-mounted device were observed, especially in the HOLOBalance in the home environment. It could be helpful for future studies for a physiotherapist to join a remote session to help patients through the process when needed. A review by Horsley et al (2020) showed that real-time video conferencing enhances the usability of the system in telerehabilitation for physiotherapy management (348).

In the HOLOBalance system, participants were required to wear body sensors (on the head, trunk, and insoles) which detected body movement and sent signals to the system for safety reasons. For example, if a patient was at risk of falls the system would ask to stop the exercise; in addition to the head-mounted device to demonstrate the hologram. From the exit interviews, participants indicated their preference to use less equipment. In the upcoming iteration of the HOLOBalance system, the number of body sensors has been reduced and insoles replaced with four IMU sensors positioned at the ankles, lower back and head. A pilot study (unpublished to date) compared the insoles/sensors used in HOLOBalance vs. IMU motion sensor data and found it to be comparable. The headset is being replaced by a lighter weight version that provides a similar segmented reality experience to the one used in this study.

Technical partners in the HOLOBalance project are continuously addressing system connectivity, delays, and feedback issues. Enhanced algorithms, including adaptive buffering and predictive data streaming, have been implemented to minimise latency and ensure more stable connectivity. These algorithms dynamically adjust to network conditions, reducing lag and ensuring seamless data transmission between components. Additionally, real-time feedback mechanisms have been optimised using advanced machine-learning techniques to analyse user actions and provide immediate, context-sensitive guidance. These enhancements are expected to significantly improve user satisfaction and system reliability.

8.4.1.1 Dynamic balance, functional gait, cognitive function, and psychosocial aspects

Following the intervention period of the HOLOBalance system (which included the MSR exercises, cognitive and auditory tasks in addition to home exercises), trends towards improvement in dynamic balance, and functional gait were noted for the HOLOBalance intervention group (both laboratory and home-based) compared to the control group. Whilst the study was not appropriately powered, this preliminary data suggests that the HOLOBalance programme may be beneficial in improving dynamic balance and functional gait for older adults at risk of falls. Achieving minimally significant changes for both is not often seen in the Otago or other fall rehabilitation programmes. However, there was no change in the cognitive and psychosocial measures.

Similar results to the feasibility of HOLOBalance system were reported in previous literature. A systematic review by Chan et al (2021) of 31 studies for telehealth, exergames, cognitive games, socialised training, and smart home systems for balance exercise showed that there was a significant improvement in balance and fall efficacy after the intervention (standardised mean difference=0.28, 95% CI 0.04, 0.53) (794). Additionally, another study aimed to investigate the effect of a home-based interactive video conferencing telerehabilitation program on balance performance in older adults (aged 65-90 years) and found that the TUG and BBS scores increased significantly in the intervention group (TUG: $P < 0.001$, BBS: $P = 0.003$) compared to the control group, however, there was no change in anxiety score in either group (i.e., Trait Anxiety Inventory) (795).

8.4.2 For stroke survivors

A Cochrane review demonstrated that the use of telerehabilitation services in stroke may help to address the lack of available long-term support and ongoing unmet rehabilitation needs to provide support to patients as they resume their lives and roles on discharge from inpatient facilities (796). Studies have shown that an additional benefit of telerehabilitation is that the data saved in the system and shared with other health professionals can promote healthcare delivery and exchange over a wider geographic distance, thereby ensuring more effective and efficient care to stroke survivors (67,797).

Due to the positive results of the HOLOBalance system among older adult populations, Chapter 7 investigated the feasibility and acceptability of using it for stroke survivors. Eight stroke survivors were recruited to study this in a laboratory-based environment only. All participants adhered to the rehabilitation programme (8-week), and only one participant dropped out for an unrelated reason. From the exit interview and the acceptability scales, the system was shown to be both feasible and acceptable. However, some difficulties were noted relating to wearing the body-worn sensors.

The current findings are consistent with a previous study by Bower et al (2015) who showed that interactive motion-controlled games for rehabilitation were clinically feasible in 40 stroke survivors (mean age was 63 years), with participants reporting that the session was enjoyable (93%), helpful (80%) and something they would like to include in their therapy (88%), and for the 4-week period with an average of seven 26-minutes, 16 participants (mean age 61 years) reported high acceptability, and noticed improvements in their functional activity (798). Additionally, a recent systematic review on telerehabilitation for neurological motor impairment in stroke, multiple sclerosis, and Parkinson's disease showed a positive impact on quality of life, satisfaction, and acceptance (799).

Technical requirements and training were the main factors influencing the delivery of stroke telerehabilitation interventions in addition to secondary factors such as platforms, support, access, cost, usability and acceptability as identified in a review for stroke survivors (800). Some technical adaptations are required for stroke survivors to increase the benefits of telerehabilitation, including providing training before the intervention, family members being around to provide support when needed (801) or caregivers being trained to help with long-term usability and engagement (797), specifically for HOLOBalance home users.

8.4.2.1 Dynamic balance, functional gait, cognitive function, and psychosocial aspects

Half of stroke survivors demonstrated >15% increased scores (i.e., improved) in post-intervention treatment for dynamic balance and functional gait measures. Studies investigating the effect of MSR exercises on balance and functional gait outcomes are limited (89) and studies combining MSR exercises with cognitive games and exergames do not exist. The preliminary findings from the current study suggest that the HOLOBalance system included the implemented exercises (MSR exercises, cognitive and auditory tasks) and the home exercise programme may result in significant improvements in dynamic balance and functional gait measures after the intervention. Further randomised controlled trials are required to confirm these findings.

Previous studies demonstrated similar findings; for instance a study on Augmented Community Telerehabilitation Intervention (ACTIV) showed improvement in general daily living functions after intervention (375). Another study found a good adherence rate (88%) and potential benefits in upper limb function (i.e., Motricity Index for upper limb and Action Research Arm Test) for stroke survivors after an intervention via the EvolvRehab-Body telerehabilitation system at patients' homes for a 12-week period, however, no change was found in hand grip force (368).

In addition to the balance training sessions by the HOLOBalance system, participants followed home exercises (the MSR exercises) including the same exercises performed in the sessions. This helped in improving balance and gait after the intervention. Home exercises are crucial for stroke survivors physical rehabilitation and help in improving functional recovery (802–804). A recent systematic review of 9 clinical trials (609 stroke participants) by Nascimento et al (2022) showed that home-based exercises helped in increasing walking speed and balance in stroke survivors (805). The home-based exercises consisted of structured and repetitive exercises targeting the paretic lower limb for improving standing and/or walking (805).

Furthermore, the exergames added in the HOLOBalance system could also help in improving balance and gait. A previous study by Huber et al (2022) showed that simultaneous-incorporated exergames were superior to single physical training in improving gait speed and walking endurance in chronic stroke survivors and were noted to be a promising type of intervention for motor-cognitive training (806). However, a potential reason for the low-range improvement in the cognitive function of stroke survivor participants after the HOLOBalance intervention could be that participants did not have mild cognitive impairments, and a ceiling effect is likely.

Adding aerobic exercises to cognitive skills training has been shown to improve cognitive function more than cognitive training alone in people with mild dementia (807) and in stroke survivors (808). It may be worthwhile to consider adding a section to the next iteration of the HOLOBalance system and to other rehabilitation programmes to promote increased PA and/or aerobic exercises, to investigate whether this provides better cognitive outcomes in stroke survivors with cognitive impairment. Furthermore, robust evidence now exists to show that PA helps to improve cognitive function scores in older adults with mild cognitive impairments (705,809,810) and in patients with mild dementia (811,812). Similarly, physically active stroke survivors showed statistically significantly lower cognitive impairments than non-active stroke survivors (813).

8.5 General limitations of current studies

An important consideration for the data presented here is that data collection was undertaken during the COVID-19 pandemic with many restrictions in place at the time, which limited both participant recruitment and face-to-face meetings (45). In particular, older adults and stroke survivors were identified as a 'vulnerable' population, and it was understandably challenging to recruit participants from this client population at this time. Therefore, all studies had a limited sample size.

8.5.1 General limitations in the methodology and statistical analysis

8.5.1.1 Population

Some potential limitations of studies on stroke physical rehabilitation include the variability and heterogeneity in the types of stroke patients, populations studied, and potential biases in participant selection. Stroke can manifest in a variety of ways and affect individuals differently, leading to challenges in creating standardised interventions that effectively address the diverse needs of stroke survivors. Additionally, the varying degrees of impairment and recovery process among individuals can make it challenging to generalise the study findings.

The findings in the current studies are relevant to ambulatory chronic stroke survivors with a motor recovery level >43 in Motricity Index and who could walk independently for 6 meters. Therefore, the findings are not applicable to stroke survivors with moderate or severe paresis and have moderate/severe cognitive dysfunction. Additionally, stroke location can have a large effect on motor, cognitive and other impairments. Most stroke survivors who participated in the studies had a stroke in the middle cerebral artery, and only one participant had a stroke in the posterior circulation and/or in the cerebellum.

In addition, aphasia is a major problem after stroke (814), participants did not had aphasia at the recruitment time, however, assessments of aphasia and protocol tailored to their needs must be addressed further in future studies. Recruited participants might have communication difficulties, which are common after strokes, albeit no aphasia (815), and this was not assessed in the current studies.

8.5.1.2 Assessment

The challenges in blinding both participants and researchers due to the nature of physical rehabilitation interventions are common. Because this work was primarily for a PhD and due to resource limitations, the assessment in study 2 (Chapter 5) of the capacity of walking at a functional level, along with the baseline assessment of the feasibility of HOLOBalance for stroke survivors (Chapter 7) was not undertaken by a blinded assessor. This was also the case for the exit interviews in Chapters 6 and 7. Future studies should look to include blinded assessors.

A major limitation in all current studies is a lack of assessment of motor impairment with a test that provides objective quantitative outcomes. For example, surface electromyography (sEMG) to identify appropriate muscle activation (600), and the use of Force Plate provide more accurate data on postural sway and balance control (559). To study cortical function, functional near-infrared spectroscopy (fNIRS) is a valuable neuroimaging approach that quantifies the change in oxygenated haemoglobin concentration between resting and active periods for each task (816). Additionally, brain mapping by functional Magnetic Reasoning Imaging (MRI) can be used to provide insights into motor progress after rehabilitation (817,818), however, because recruitment was undertaken during the COVID-19 pandemic, the use of these tests was challenging.

8.5.1.3 Sample size and statistical analysis

Generally, limitations in research can be due to maturation bias, confounding variables, attrition of subjects, statistical regression toward the mean, and multiple tests of significance (819). Due to the non-normal distribution of the data in the current studies, the results were analysed using non-parametric statistics tests which are less powerful than parametric tests and provide limited assumptions based on the analysis of the ranks methods (820). Whilst appropriate statistical analyses were undertaken, there is a need to include a larger sample and perform more detailed analyses.

8.5.2 Specific limitations in the methodology of each study

Systematic reviews include the potential for publication bias, where only certain studies meeting specific criteria are included, leading to a skewed representation of the available evidence. Additionally, the quality of included studies impacts the overall conclusions drawn from the review. Systematic reviews are also limited by the existing body of literature; if there are only a few studies on a particular topic, the review's findings may be constrained by this limited evidence.

Limitations in correlation studies also include not accounting for potential confounding variables that could influence the relationship between the variables being studied (821,822), for example, personal factors. Furthermore, it can be difficult to control other relevant variables, such as environmental factors. The findings in Study 2 (Chapter 5) are limited by the participants' criteria, which were motor recovery > 43 in the Motricity Index, able to walk 6 meters, and no moderate or severe cognitive impairments, depression, anxiety, or dizziness. Other factors potentially affecting walking at a functional level which were not included in the study because of the limited sample size. For example, there is a need to identify the type and purpose of walking aids, for instance whether it is only for safety or needed to help with functionality (190,823,824). In addition, it is important to know if participants have other health conditions (i.e., comorbidity) (825,826), the medications used, in addition to body mass index (827,828), and lifestyle behaviour before a stroke.

In terms of the feasibility studies for the HOLOBalnce system; these studies are critical for developing novel and complex projects (829). However, , there is limitations of blinding due to the nature of the interventions for the treatment provider and patients, and potential selection bias in rehabilitation studies. In addition, feasibility studies lack a long-term assessment of sustainability and scalability of the proposed intervention (830). The follow-up assessment period was limited to 3 months, and a prolonged follow up period is recommended. Additionally, the follow up was for fall incidence but should also include balance control and functional gait assessment.

One of the limitations of telerehabilitation is health equity, which is the ability for everyone, regardless of social or economic background, to get the healthcare they require. Patients with low socio-economic backgrounds may lack video-sharing technology, such as a smartphone, tablet, or computer, and lack internet access. Although the equipment can be provided by a provider, because of lack of knowledge and experience, they may require further support to ensure health equality in telerehabilitation (831).

8.5.3 The impact of the COVID-19 pandemic on the current studies

Multiple severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was recorded in Wuhan, China in December 2019. After a rapid increase of these cases, the incidence was reported to the World Health Organisation (WHO) to take urgent action. Then on 6 January 2020, a novel coronavirus was identified. On the 30th January 2020, the WHO declared a public health emergency of international concern and later labelled it as a Coronavirus disease 2019 (COVID-19) outbreak pandemic. The government in the United Kingdom (UK) decided to set a lockdown on the 23rd of March 2020 to minimise the spread of COVID-19.

The virus spread rapidly across the globe, causing sickness, death, economic disruption, and societal changes on an unprecedented scale. From overwhelmed healthcare systems and widespread disruptions to travel restrictions and lockdowns. On an individual level, many people have experienced illness, loss of loved ones, isolation, anxiety, and mental health issues.

The lockdown due to COVID-19 had significant consequences for this doctorate project. All PhD students were asked by King's College London (KCL) to sign their consent that research would pause or continue remotely where possible from 23 March 2020 onwards. I had to return to Saudi Arabia by May 2020 and was in isolated quarantine for a couple of weeks. After the release of lockdown restrictions in September 2020, I decided to travel back to the UK and was also in quarantine after travelling.

The ethical approval for study 2 was postponed due to priorities being provided to studies related to COVID-19. At the time and during the first lockdown period in the UK from February to September 2020, I have started with the first study (the systematic review).

Afterward, when face-to-face appointments were allowed, many personal protective equipment (PPE) restrictions were in place. Laboratories for testing and rehabilitation were open and bookable but with limited access during the week for no more than two participants a day with 2 hours gap in between. This increases the challenges of booking a convenient appointment for participants.

During the second lockdown period in the UK between September 2020 to April 2021, the recruitment for study 2 and 3 was initiated. The recruitment of older adults at risk of falls and stroke survivors was restricted and limited, therefore I recruited healthy controls for study 2. Older adults and stroke survivors were classified as 'vulnerable' and at high risk of infection even after the ending of restrictions (72,557). Even after the lockdown period was ended, most older adults at risk of falls and stroke survivor volunteers found it challenging to attend twice sessions a week for 10 weeks for the feasibility of the HOLOBalance system (study 3 and 4) during the pandemic.

The time frame for all PhD students for their whole project was automatically extended during the pandemic by three months because face-to-face data collection at the university was not possible for PhD students for one year. In the end, the sample size target was not reached for study 2 and 3, where, instead of 50 for each group, 20 participants were recruited. For study 3, only 15 participants were recruited and to increase the sample size, participants from other research centres were included in the analysis of the secondary objectives. For study 4, instead of 10, only 8 participants were recruited. The small sample size limits the statistical analysis and had a significant impact on the quality of all experimental studies.

8.6 Recommendations for future research

Further studies are needed to improve the psychometric properties of OMs used for assessing dynamic balance, functional gait, and DT walking tests. This is in addition to addressing the challenges required for optimal functional recovery, more specifically for stroke survivors' needs such as turning while walking.

Identifying the factors associated with walking at a functional level can help in tailoring individualised assessment and treatment for ambulatory stroke survivors. In the current study, balance confidence (i.e., Activities-specific Balance Confidence scale) had a significant association with walking at a functional level (i.e., Mini-BEST test, FGA), therefore, assessment of balance confidence can be recommended in screening and addressing in treatment protocols. Further studies using a larger sample size are required to confirm the association and to include other measures for assessing balance confidence, for example, interviews to reveal if patients have specific views that impede their confidence in walking at a functional level. Similarly, further research is required to investigate adding strategies to improve balance confidence for instance cognitive behavioural therapy to the treatment protocol for ambulatory chronic stroke survivors.

Since there is a large heterogeneity among stroke survivors, classification into subgroups according to their problems and needs will help in identifying specific factors associated with walking at a functional level. In the current study, participants had no dizziness or vertigo, however, there is a need for further studies to assess the SVV in stroke survivors who experienced dizziness or vertigo and investigate whether there is an association with walking at a functional level.

Existing evidence has shown that there is an association between moderate or severe cognitive dysfunction and functional mobility (832–835), however further research is required to assess the association with mild cognitive dysfunction. Potentially the most common affected function in mild cognitive impairment in stroke survivors is visuospatial attention or short-term memory, which was not associated with walking at a functional level (i.e. as assessed by the Mini-BESTest, FGA scores), but has an impact on patient quality of life and needs further study. For example, a minor problem such as when a patient is lost with directions and cannot walk independently to reach their destination can be related to cognitive dysfunction. This can be exhausting and increase the difficulty of walking at a functional level (i.e., walking for long distances in a busy area which needs high motor functional ability such as abruptly changing direction and walking at different speeds).

The balance training delivered by the HOLOBalance system with AR for older adults at risk of falls and ambulatory stroke survivors was safe, feasible, and acceptable by participants. Participants achieved good adherence rates to exercise and trends towards greater balance control and functional gait were observed. This endorses the results of larger randomized controlled studies. Some practical recommendations arising from the preliminary data of the HOLOBalance system from the current studies to enhance engagement with the system include providing a workshop for participants before the intervention, running video conference calls when needed, and using a lighter head mounted device. The usability of the HOLOBalance system at home can be increased by a caregiver helping with preparation such as changing the sensor batteries. Further studies are required to assess cost-effectiveness compared to traditional rehabilitation methods.

8.7 Recommendations and implications for clinical practice

The gaps between clinical research and practical applications in rehabilitation of stroke survivors are considerable. Some of the notable gaps include challenges in translating research findings from clinical settings into real-world rehabilitation settings and into different patient populations (836). Key recommendations for clinical practice include provide more individualised assessment and treatment plans to meet the specific needs and abilities of each stroke patient. For example, to improve walking at a functional level for ambulatory chronic stroke survivors, there is a need to assess the patient's motor function, balance, gait, and overall functional abilities, to set up a more personalised rehabilitation program.

Additionally, greater multidisciplinary collaboration between neuropsychologists and other healthcare professionals can provide a comprehensive assessment to address the varied challenges faced by stroke patients. For example, cognitive screening with a rapid tool such as the MoCA tool can be useful, but there is a need for a thorough cognitive assessment particularly to develop and improve the cognitive tests in the DT walking assessment.

Home exercise programmes are essential for optimal functional recovery for older adults at risk of falls and stroke survivors (339,802). The use of technology such as VR or AR offers innovative ways of delivering exercises and would increase the integration, enjoyment, and engagement in exercise rehabilitation.

8.8 Overall Conclusions

In conclusion, the main purposes of the current studies were: 1) to identify the optimal OM based on psychometric properties for assessing walking at a functional level; 2) to assess the capacity and identify factors associated with walking at a functional level for ambulatory stroke survivors in comparison to healthy controls; and 3) to study the feasibility of a telerehabilitation — HOLOBalance system — for providing individualised balance training for older adult at risk of falls and for ambulatory chronic stroke survivors.

The studies included in the current systematic review provided insight into the most suitable currently available OMs for assessing walking at a functional level - which includes dynamic balance, functional walking, and DT while walking. All psychometric properties including reliability, validity, and responsiveness were tested for dynamic balance OM; the Balance Evaluation System Test (BESTest) and (Mini-BESTest) demonstrated the best psychometrics in this category. In the functional walking category, the Dynamic Gait Index (DGI) and Functional Gait Assessment (FGA) demonstrated the best psychometric properties.

To test cognitive-motor interference, DT tests should be considered. In the current review only three studies for DT tests were included, up to now studies on DT tests for ambulatory chronic survivors are limited. Moreover, only the reliability and validity were tested for this category. The reliability of cognitive tasks while performing the walking tests was lower than the reliability of motor-tasks tests, which could be due to difficulty in assessing cognitive function while walking tests. This also indicates the need for further studies to develop and improve tests of cognitive tasks while walking for stroke survivors. Future research on clinical physiotherapy OMs for ambulatory chronic stroke survivors need to develop DT tests and test their psychometric properties. This will help in assessing ambulatory stroke survivors for higher functional activity level.

Moreover, further studies are needed to investigate untested properties such as minimum detectable change. In addition, future studies are required to improve the available OM to address the specific needs of stroke survivors. For more efficient use of OM in clinical practice and in research, should be specific to their individual level and needs. This will allow for a more coherent understanding of treatment efficacy, but will also allow for parity across studies and comparisons between various rehabilitation programmes.

In study two, ambulatory chronic stroke survivor participants demonstrated significant limitations in the dynamic balance control and functional gait in comparison to healthy controls. Additionally, Balance confidence is an important factor which demonstrated a positive association with both the Mini-BESTest and the FGA. This provides insight to include balance confidence in the assessment and treatment for ambulatory stroke survivors, which will help in providing more personalised rehabilitation. Further studies with a larger sample are needed to study the association between mild cognitive dysfunction, SVV, psychological status and quality of sleep, and both the Mini-BESTest and the FGA.

Meanwhile, traditional balance training consists of sets of exercises, defined by a healthcare professional, which can be performed daily in a home environment. Cochrane reviews and NICE guidelines have highlighted that balance and gait physiotherapy is the only effective treatment for limitations in balance control and functional gait. However, although exercises are brief and easy to perform, there is up to a 50% loss in follow-up rate in older adults and stroke survivors in these programmes. Although supervision significantly increases compliance and effectiveness, it is costly to provide. Therefore, many fall-prevention, balance, and stroke rehabilitation programmes rely upon participants performing exercises independently at home (690,837).

Moreover, rehabilitation programmes focus most often on a specific component of balance and are not multisensory or multifactorial, and do not focus on vestibular exercises. Most rehabilitation exercises are static balance tasks, despite most falls occurring during dynamic motion. Exercise rehabilitation needs to address all balance components to provide a multifactorial exercise programme, including multisensory exercises to stimulate vestibular system function and challenge balance from different positions. Further, there is a need to include cognitive training.

Study three and four aimed to determine the feasibility of a novel telerehabilitation system (HOLOBalance). The HOLOBalance system uses a hologram to deliver the balance training (MSR exercises, cognitive training games, and exergames) and the exercises can be prescribed individually.

The feasibility of the system was tested for older adults at risk of falls in home and clinic environments and for ambulatory stroke survivors in clinic settings. The exit interviews and the usability scales indicated that the HOLOBalance system was feasible and acceptable by participants. However, the scores for usability scales were lower for the home environment because of the difficulties in handling the equipment, for example wearing the insole sensors. The next iteration of the HOLOBalance system will use a sensor placed on the calf and lighter head-mounted device.

Trends towards improvements in the Mini-BESTest and the FGA were observed after the intervention of the HOLOBalance system. Early results were promising for older adults at risk of falls and ambulatory chronic stroke survivors. Further studies with larger samples are needed to investigate the efficacy of the HOLOBalance system.

Finally, the work presented in this thesis has provided new information on rehabilitation for ambulatory chronic stroke survivors. Recovery of walking safely in the community for ambulatory chronic stroke survivors requires individualised assessment and rehabilitation. There is a need to assess walking at a functional level in challenging situations, such as adding DT walking tests to regular assessment. The systematic review showed that the most tested psychometric properties in the included OMs were validity and reliability, but studies for responsiveness were limited. Furthermore, the clinical physiotherapy assessment should also include non-physical factors such as balance confidence. This will help in goal setting and treatment according to each patient's needs. Meanwhile, the use of telerehabilitation - through the HOLOBalance system - for balance training was feasible and acceptable for balance training for older adults at risk of falls and ambulatory chronic stroke survivors. The efficacy of the HOLOBalance system need to be studied in further research with larger samples.

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Appendices

Appendix 1. An example of a search strategy in MEDLINE

```
Your autoalert was checked against the latest changes but no relevant documents were found.
Total documents retrieved: 0

Results Generated From:
Ovid MEDLINE(R) ALL <1946 to November 08, 2022>
        Ovid MEDLINE(R) <October Week 5 2022> (updates since 2022-11-07)
Ovid MEDLINE(R) ALL <1946 to November 08, 2022>
        Ovid MEDLINE(R) Epub Ahead of Print <November 08, 2022> (updates since 2022-11-07)
Ovid MEDLINE(R) ALL <1946 to November 08, 2022>
        Ovid MEDLINE(R) Daily Update <November 08, 2022> (updates since 2022-11-07)
Ovid MEDLINE(R) ALL <1946 to November 08, 2022>
        Ovid MEDLINE(R) PubMed-not-MEDLINE <November 08, 2022> (updates since 2022-11-07)
Ovid MEDLINE(R) ALL <1946 to November 08, 2022>
        Ovid MEDLINE(R) PubMed-not-MEDLINE <2022 to October 27, 2022> (updates since 2022-11-07)
Ovid MEDLINE(R) ALL <1946 to November 08, 2022>
        Ovid MEDLINE(R) In-Process & In-Data-Review Citations <November 08, 2022> (updates since 2022-11-07)



Set   Search                                                            Results
---------------------------------------------------------------------------------
001   exp Patient Outcome Assessment/                                     1315
002   exp Outcome Assessment, Health Care/                               27874
003   (outcome adj3 measure*).mp. [mp=title, book title, abstract,       22978
       original title, name of substance word, subject heading wor
      d, floating sub-heading word, keyword heading word, organism
       supplementary concept word, protocol supplementary concept
      word, rare disease supplementary concept word, unique identi
      fier, synonyms]
004   (measur* adj3 tool).mp. [mp=title, book title, abstract, ori        1435
      ginal title, name of substance word, subject heading word, f
      loating sub-heading word, keyword heading word, organism sup
      plementary concept word, protocol supplementary concept word
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005	scale.mp.	97307
006	1 or 2 or 3 or 4 or 5	139290
007	exp Psychometrics/	2136
008	(psychometr* adj3 propert*).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	3660
009	(psychometr* adj3 effect*).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	15
010	reliabilit*.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	18902
011	validit*.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	17204
012	responsiveness.mp.	4786
013	appropriateness.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	2101
014	precision.mp. [mp=title, book title, abstract, original titl	18010

015	interpretability.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	1221
016	acceptability.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	6508
017	feasibility.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	23709
018	7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17	79660
019	exp Postural Balance/	662
020	exp Posture/	752
021	exp Gait/	1366
022	exp Walking/	2109
023	balance.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	19546
024	(postur* adj3 control).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	728

025	stability.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	49527
026	step*.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	54883
027	(body adj3 equilibrium).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	17
028	stand*.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	131078
029	(static adj3 control).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	87
030	(dynamic adj3 control).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	494

031	function* task.mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	72
032	(function* adj3 activit*).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	3385
033	19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30 or 31 or 32	244118
034	exp Stroke Rehabilitation/	760
035	exp Hemiplegia/	85
036	exp Paresis/	132
037	exp Cerebral Hemorrhage/	648
038	exp Ischemic Attack, Transient/	255
039	exp Cerebral Infarction/	739
040	exp Brain Ischemia/	2482
041	cerebrovascular accident*.mp.	571
042	34 or 35 or 36 or 37 or 38 or 39 or 40 or 41	4499
043	6 and 18 and 33 and 42	29
044	limit 43 to english language	28
045	from 44 keep 19	1
046	limit 45 to updaterange="medl(20221107215912-20221102181429],medp(20221107215912-20221108221316],mesx(20221107215912-20221108204300],pmnm(20221107215912-20221108215058],pmnm6(20221107215912-20221108212751],prem(20221107215912-20221108215740]"	0

Appendix 2. Quality assessment tables for the included studies in the Systematic Review

Table A. Quality assessment of reliability, measurement error and validity for the studies of dynamic balance outcome measures.

Table B. Quality assessment of responsiveness for the studies of dynamic balance outcome measures.

Table C. Quality assessment of reliability, measurement error and validity for the studies of functional gait OMs (Group A).

Table D. Quality assessment of reliability, measurement error and validity for the studies of functional gait OMs (Group B).

Table E. Quality assessment of responsiveness for studies of functional gait OMs (Group A &B).

Table F. Quality assessment of reliability, measurement error and validity studies for dual task walking OMs.

Walking test	**Reliability**					**Measurement error**			**Validity**				
(Author, year)	Type of reliability	n	MD	SM	SO	MD	SM	SO	Type of validity	n	MD	SM	SO (Correlation with)
BESTest & Mini-BESTest (Chinsongkram et al., 2014)	Intra-rater	12 S 5PT	-	+	$ICC_{3,k}$ = 0.99				Construct	67 S	++	++	BBS rho= 0.96 PASS rho= 0.96 CB&M rho = 0.91 Mini-BESTest rho= 0.96
	Inter-rater		-	+	$ICC_{3,k}$ = 0.99				Known-group	Low function (LF)n=35 High function (HF)n=35	++	++	Floor effect: BESTest:0% Mini-BESTest: 34.3% LF Ceiling effect: BESTest: 4.3% for LF & HF Mini-BESTest: 4.3% for both.
BESTest (Rodrigues et al, 2014)	Intra-rater	16 S	0	+	ICC = 0.98				Construct	16 S	++	++	BBS *r*= 0.78 ABC scale *r*= 0.59
	Inter-rater	2 raters	+	+	ICC = 0.93								
BESTest (Sahin et al, 2019)	Internal consistency	50 S	0	++	Cronbach's α= 0.96				Construct	50 S	++	++	Postural stability *r*= -0.62 Limits of stability *r*= 0.60 BBS *r*= 0.91 ABC scale *r*= 0.887
									Known-group	Fallers n= 26 S Non fallers n=24 S	++	++	AUC= 0.84 Cut-off point (fallers & non fallers) 69.44% of total score
Mini-BESTest (Tsang et al, 2013)	Internal consistency	106 S	0	++	Cronbach's α= 0.94				Construct	106 S	++	++	BBS rho= 0.83 FRT rho= 0.55 OLS rho= 0.54 TUG test rho= -0.82
	Intra-rater	106 S	++	++	$ICC_{(3,1)}$= 0.97								

		1 rater											ABC rho= 0.50
	Inter-rater	106 S 2 raters	++	++	ICC $_{(2,1)}$= 0.96				Known-group	106 S 48 H	++	0	Statistically significant difference at P≤0.001 (Mann-Whitney U test)
										Fallers n= 25 S Non fallers n= 81 S	++	++	AUC= 0.64 Sensitivity 64% Specificity 64.2% Cut-off score (fallers & non fallers) is 17.5
Mini-BESTest (Miyata et al, 2020)									Construct	88 S	+	+	Comfortable speed *r*= 0.70
									Known-group	Fast n=61 S Slow n=27 S	++	++	AUC= 0.87 Cut-off score (fast & slow walkers) is 17.5
Mini-BESTest (Madhavan & Bishnoi, 2017)									Construct	n=41 S	++	++	BBS *r*= 0.70 10mWT *r*= 0.58
									Known-group	Fast n= 16 S Slow n= 25 S	++	++	AUC= 0.81 ± 0.06 Cut-off score (fast & slow walkers)18.5 out of 28.
Three shortened versions of BESTest (Winairuk et al, 2019)	Intra-rater	12 S 5 PT	-	+	Short ICC $_{(3,5)}$ = 0.98 Brief ICC $_{(3,5)}$ = 0.98 Mini ICC $_{(3,5)}$ = 0.98				Criterion	70 S	++	-	Shortened version with the original BESTest. BESTest rho= 0.96 Short rho= 0.95 Brief rho= 0.93 Mini rho= 0.95
	Inter-rater		-	+	Short ICC $_{(3,5)}$ = 0.95 Brief ICC $_{(3,5)}$ = 0.98 Mini ICC $_{(3,5)}$ = 0.98								
Brief-BESTest (Huang & Pang 2016)	Internal consistency	27 S	0	++	Cronbach's alpha = 0.82				Construct	50 S	++	++	BBS rho= 0.87 PASS rho= 0.91 CMSA rho= 0.58
	Intra-rater	2 PT	-	+	ICC $_{(2,1)}$ = 0.97	-	++	SEM= 0.82					

	Inter-rater		++	+	ICC $_{(2,1)}$ = 0.97	++	++	SEM= 0.77					FMA-LE rho= 0.66 MoCA rho= 0.44 GDS rho= - 0.15
									Known-group	50 S 27 H	++	++	Stroke and healthy AUC= 0.94 cut off score < 18 Walk with or without aids AUC= 0.81 cut off score <14
Mini-BESTest Short BESTest (Miyata et al, 2022)	Internal consistency	115 S 5 PT	++	++	Separation index (G) Mini-BESTest G = 3.7 Short BESTest G = 2.88				Internal construct validity	115 S	++	++	Mini-BESTest: item difficulty spread evenly. Short BESTest: skewed toward the low difficulty level.
CB&M scale (Knorr et al, 2010)									Construct	44 S	++	++	BBS rho= -0.83 TUG test rho= -0.75
CB&M scale (Miller et al, 2016)									Structural	283 scores	+	++	Stroke-specific 14-item scale (CB&M Stroke)
FSST (Goh et al, 2013)	Intra-rater	15 S 15 H 2 raters	-	++	ICC $_{(3,1)}$ = 0.83				Construct	15 S	++	++	BBS *r*= -0.28 Level of stability *r* =0.64 TUG test *r* =0.59
	Inter-rater		+	+	ICC $_{(3,1)}$ = 0.99				Known-group	15 S 15 H	++	++	sensitivity 73.3%; specificity 93.3%. AUC=0.87; P<.001 Cut-off score (healthy & stroke) 11 sec.

Table A. Quality assessment of reliability, measurement error and validity for the studies of dynamic balance outcome measures. Activities-specific Balance Confidence scale (ABC scale). Berg Balance Scale (BBS). Balance Evaluation System Test (BESTest). Community balance and mobility scale (CB&M) scale. Fugl-Meyer Motor Assessment-Lower Extremity (FMA-LE). Functional reach test (FRT). Geriatric Depression Scale-Short Form (GDS). Healthy participants (H). Methodological Design (MD). Montreal Cognitive Assessment (MoCA). Sample size(n). One Leg Standing (OLS). Postural Assessment Scale for Stroke patients

(PASS). Pearson's correlation (*r*). Spearman's corelation (rho). Stroke survivors (S). Short version of BESTest (S-BESTest). Statistical Method (SM). Statistical outcome (SO). COSMIN grading system: very good (++), adequate (+), doubtful (0), inadequate (-).

Walking test	**Responsiveness**				
(Author, year)	Approach	n	MD	SM	SO
BESTest & Mini-BESTest[30]	Construct	49 S	++	++	Ceiling effect before rehabilitation & after rehabilitation BESTest 0%, Mini-BESTest 0% Internal responsiveness: BESTest SRM= 1.2, number of participants with no change: 6% Mini-BESTest SRM= 0.9, number of participants with no change: 26% External responsiveness: BESTest AUC= 0.92, cut-off score is 10% Mini-BESTest AUC= 0.89, cut-off score is 3 points
Mini-BESTest[32]	Construct	88 S	++	++	Absolute mean gain (SD), Relative mean gain (SD)= FAC 2-3 points (n=22): 2.4 (3.3), 14.1 (16.8), P value= 0.087 FAC 4-5 points (n=44): 3.1 (3.2), 16.2 (15.5), P value< 0.001 FAC 6 points (n=22): 2.9 (2.5), 13.0 (11.9), P value< 0.001
BESTest short forms[33]	Criterion	70 S	NA	++	External responsiveness Minimal clinical important differences were calculated.
	Construct		0	++	**Internal responsiveness:** after 4 weeks, floor and ceiling effect (%). BESTest: (0.0), (4.3); Short BESTest: (0.0), (11.4), Brief bestEST: (0.0), (15.7), Mini-BEST: (0.0), (7.1)
BESTest, Mini-BESTest, Brief BESTest (Hasegawa et al, 2021)	Construct	30 S	+	++	BESTest ES= 0.56, SRM= 1.28, RE= 0.99, cutoff score is 16.7% of the BESTest score, AUC= 0.77 Mini-BESTest ES= 0.69, SRM= 1.17, RE= 0.83, cutoff score 5.5 points from the Mini-BESTest score, AUC= 0.82 Brief BESTest ES= 0.41, SRM= 0.75, RE= 0.35, cutoff score 1.5 ponts from the Brief BESTest score, AUC= 0.77
CB&M[34]	Construct	44 S	++	++	SRM= 0.83
CB&M[35]	Construct	238 S	+	++	between discharge and 6-month SRM= 0.63, between 6-month and 12-month SRM= 0.73

Table B. Quality assessment of responsiveness for the studies of dynamic balance outcome measures. Balance Evaluation System Test (BESTest). Community balance and mobility scale (CB&M) scale. Effect size (ES). Healthy participants (H). Methodological Design (MD). Sample size (n). Statistical Method (SM). SO: Statistical outcome. S: stroke survivors. S-BESTest: short version of BESTest, SRM: Standard Response Mean. RE: Relative efficiency. COSMIN grading system: very good (++), adequate (+), doubtful (0), inadequate (-).

Walking test	**Reliability**					**Measurement error**			**Validity**				
(Author, year)	Type of reliability	n	MD	SM	SO	MD	SM	SO	Type of validity	n	MD	SM	SO
L-shape walk test (Kim et al, 2015)	Intra-rater	33 S	0	++	ICC $_{(3,1)}$ = 0.99	+	++	SDC$_{95}$ = 4 sec	Construct	33 S	++	++	**TUG** test r = 0.89 **10mWT** r = 0.88 **2 min WT** r = -0.91
	Inter-rater	2PT	+	++	ICC $_{(2,1)}$ = 0.99								
Parallel walk test (Ng et a l, 2015)	Test-retest	37 S	+	++	ICC $_{(3,2)}$ (Time) =0.93 ICC $_{(3,2)}$ (Score) = 0.98				Construct	37 S	++	++	FMA Time rho= -0.51 Score r= -0.38 **FSST** Time rho= 0.58 Score rho= 0.40 **BBS** Time rho= -0.62 Score rho= -0.68 **10mWT** gait speed Time rho= - 0.85 Score r= -0.61 **TUG test** Time rho= 0.84 Score rho= 0.81
	Intra-rater	37 S 2 R	0	++	ICC $_{(3,1)}$ (Time) = 0.96 ICC $_{(3,1)}$ (Score) = 0.91								
	Inter-rater	37 S 2 R	+	++	ICC $_{(2,2)}$ (Time)= 0.99- 1.00 ICC $_{(2,2)}$ (Score)= 0.97 -0.99								
Sideways walk test (Ng et a l, 2015)	Test-retest	29 S 2 R	+	++	ICC $_{(3,2)}$ (Time) = 0.99 ICC $_{(3,2)}$ (Score) = 0.99	+	++	SDC=1.85 sec	Construct	29 S	++	++	**FMA** Time rho= -0.74 Step Count rho= -0.67 **FSST** Time rho= 0.57 Step count rho= 0.60 **BBS** Time rho= -0.62 score rho= -62 **ABC scale** Time rho= -0.67 Step count rho=0.73 **TUG test** Time rho= -0.29 Step count rho= -0.33

Sideways walk test (Ng et a l, 2015)	Intra-rater		-	++	ICC $_{(3,1)}$ (Time) = 0.96 ICC $_{(3,1)}$ (Score) =0.97								
	Inter-rater		+	++	ICC $_{(2,2)}$ (Time)= 0.99 ICC $_{(2,2)}$ (Score)= 0.99								
Standardised walking obstacle course test (Ng et al, 2017)	Test-retest	29 S 2 R	+	++	ICC $_{(3,2)}$ (Time)= 0.97 ICC $_{(3,2)}$ (Score)= 0.97	+	++	SDC= 3.9 sec SDC= 4 steps	Construct	29 S 30 H 2 R	++	++	**FMA** Time rho= -0.47 Step count rho= -0.34 **BBS** Time rho= -0.40 Step count rho= -0.29 **FSST** Time rho= 0.26 Step count rho= 0.06 **TUG test** Time rho= 0.77 Step count rho= 0.63
	Intra-rater		0	++	ICC $_{(3,1)}$ (Time) = 0.96 ICC $_{(3,1)}$ (Score) = 0.95								
	Inter-rater		+	++	ICC $_{(2,2)}$ (Time)= 0.99 ICC $_{(2,2)}$ (Score)= 0.99								
Long-Distance Corridor Walk Test	Test-retest	25 S 2 R	+	++	ICC $_{(3,1)}$ (Time) = 0.97 ICC $_{(3,1)}$ (Step count) = 0.97	+	++	SDC= 4.8 sec SDC= 6.6 Steps SDC= 18.7m	Construct	25 S 25 H	++	++	**FMA** Time rho= -0.63 Step count rho= -0.44 **BBS** Time rho= -0.57 Step count rho= -0.54 **TUG test** Time rho= 0.83

(Ng et al, 2020)	Inter-rater		+	++	ICC $_{(2,1)}$ (Time)= 0.99 ICC $_{(2,1)}$ (Step count) = 0.99								Step count rho= 0.76
The Timed 180^{O} Turn Test (Robinson & Ng, 2018)	Test-retest	33 S 2R	+	++	ICC $_{(3,2)}$ (Time) = 0.98 ICC $_{(3,2)}$ (Step count) = 0.97	+	++	SDC $_{95}$ (T)= 0.62sec SDC $_{95}$ (SC)= 0.83 steps	Construct	33 S 32 H	++	++	**FMA** Time rho= -0.62 Step count rho= -0.46 **FSST** Time rho= 0.57 Step count rho= 0.39 **BBS** Time rho= -0.65 Step count rho= -0.57 **TUG test** Time rho= 0.71 Step count rho= 0.51 **ABC scale** Time rho= -0.36 Step count rho= -0.28
	Intra-rater		0	++	ICC $_{(3,1)}$ (Time) = 0.97 ICC $_{(3,1)}$ (Step count) = 0.96								
	Inter-rater		+	++	ICC $_{(2,2)}$ (Time)= 0.97 ICC $_{(2,2)}$ (Step Count) = 0.98								
The Cone Evasion Test (Sjoholm et al, 2019)	Intra-rater	20 S 10 PT	-	++	ICC $_{(2,1)}$ = 0.98				Construct	221 S	++	++	**FAC** rho= -0.67 **TUG** test rho= 0.45 **TUG** test cog. rho= -0.04 **MoCA** rho= - 0.36 Star cancellation rho= -0.36
	Inter-rater		0	++	ICC $_{(2,1)}$ = 0.96								
Figure-of-Eight walk test (Wong et al, 2020)	Test-retest	35 S 29 H 2 R	+	++	ICC $_{(2,1)}$ = 0.98				Construct	35 S	++	++	**FMA** rho= -0.72 Muscle strength *r*= -0.46 **FSST** rho= 0.53 **10mWT** rho= 0.91 **TUG** test rho= 0.87 **BBS** rho= -0.70 **ABC** scale rho= -0.25
	Intra-rater		0	++	ICC $_{(3,1)}$ = 0.96								
	Inter-rater		+	++	ICC $_{(3,2)}$ = 0.99								
Six-Spot Step Test (Lindvall et al, 2020)	Test-retest reliability	81 S 5 PTs	+	++	ICC $_{(2,1)}$ = 0.96	+	++	SEM= 3.42 sec SRD= 9.48 sec	Construct	81 S	++	++	**DGI** rho= -0.83 **FSST** r= 0.86 **TUG** test r= 0.92

													Sit to Stand r= 0.57 **ABC** rho= -0.59
Six -Spot Step Test (Liu et al, 2021)	Test-retest	25 S 2 PT	+	++	ICC $_{(3,1)}$ = 0.93	+	++	SEM= 2.18 sec MDC= 6.05 sec	Construct	25 S	++	++	**BBS** rho= -0.53 **FMA** rho= -0.52 **TUG** test rho= 0.83
	Intra-rater		+	++	ICC $_{(3,1)}$ = 0.96								
	Inter-rater		+	++	ICC $_{(2,1)}$ = 0.99				Known group	25 S 25 H	++	++	Stroke: 14.97sec Healthy: 8.05sec (*P*< .001) Cut-off score 10.11 sec
3-meter Backward Walk Test (Kocman et al, 2021)	Test-retest	41 S	0	++	ICC $_{(2,1)}$ = 0.98	0	++	SEM= 1.11sec MDC= 1.57sec	Construct	41 S	++	++	**BBS** r= 0.69 **TUG** test r= 0.85
3-meter Backward Walk Test (Demark et al, 2022)	Intra-rater	Subacute 28 S Chronic 25 S	0	++	Subacute ICC $_{(2,1)}$ = 0.96 Chronic ICC $_{(2,1)}$ = 0.94	0	++	Subacute SEM= 0.02m/s MDC= 0.07m/s Chronic SEM= 0.04m/s MDC= 0.11m/s	Construct	Subacute 34 S Chronic 29 S	++	++	Time from GAITRite ICC $_{(2,1)}$= 0.96 ICC $_{(2,1)}$= 0.97
	Inter-rater		0	++	Subacute ICC $_{(2,1)}$ = 0.99 Chronic ICC $_{(2,1)}$ = 0.99								
TUG test (Nair et al, 1999)	Test-retest	33 S	+	+	ICC= 0.96				Construct	33 S	-	++	**BI** rho = -0.66
TUG test (Ng & Hui-Chan, 2005)	Test-retest	11 S	+	++	ICC = 0.95				Construct	10 S	++	++	Step length rho= -0.67 Stance time rho= -0.60
									Known group	11 S 10 H	-	-	Stroke: 22.6±8.6 Healthy: 9.1±1.6

													(*P*< .001)
TUG test (Alghadir et al, 2018)	Test-retest	56 S	0	++	ICC $_{(2,1)}$ = 0.98	0	++	SEM=1.16 sec SDC= 3.2 sec	Construct	56 S	+	++	**DGI** *r*= -0.48 **BBS** *r*= -0.53
TUG test (Johansen et al, 2016)	Intra-rater	60 S	-	++	ICC $_{(2,1)}$ = 0.96	-	++	SEM=1.3 sec SDC = 3.6 sec					
TUG $_{motor}$ test (Chan et al, 2017)	Test-retest	33 S 2 R	+	++	ICC $_{(3,1)}$ = 0.98	+	++	SDC= 3.53 sec	Construct	33 S 32 H	++	++	**FMA** Time *r*= -0.69 Step count *r*= -0.57 **BBS** Time *r*= -0.63 Step count *r*= -0.53 **ABC** Time *r*= -0.35 Step count *r*= -0.31
	Intra-rater		0	++	ICC $_{(3,1)}$ = 0.97								
	Inter-rater		+	++	ICC $_{(3,2)}$ = 0.99								
									Construct	33 S	++	++	**FSST** Time *r*= 0.51 Step count *r*= 0.32 **TUG test** Time *r*= 0.74 Step count *r*= 0.61
Expanded TUG test (Faria et al, 2012)	Intra-rater	48 S 3 R	0	++	ICC = 1								
	Inter-rater		0	++	ICC = 0.99								
TUG – Assessment of Biomechanical Strategies (ABS) (Faria et al, 2013) a	Intra-rater	22 S 8 R	-	++	Sit to stand *K* = 0.67-1 Gait items *K* = 0.94-1 Turn items *K* = 0.89-1				Content	13 S 8 R	0	++	Sit to stand *K* =0.72-1 Git items *K* =0.52-1 Turn items *K* =0.52-1
	Inter-rater		-	++	Sit to stand *K* =0.11-0.95 Gait items *K* = 0.56-0.91				Criterion	13 S	NA	++	Sit to stand from computerized motion analysis systems *K* =0.09-1

					Turn items *K* = 0.59-0.86						
TUG – ABS (Faria et al, 2013) b	Inter-rater	44 S	0	++	*K* = 0.80		Criterion	44 S	NA	++	Sit to stand *K (*R2) = 0.53-0.84 Gait parameters *K (*R2) = 0.35-0.64 Turn *K (*R2) = 0.29-0.69
							Construct		++	++	**TUG** test time *r*= -0.8
							Known group	48 S 48 H	++	++	**TUG-ABS** & TUG test % Stroke 97.9%
							Construct	Fast n=25 S Slow n= 9 S	++	++	**TUG-ABS** & TUG test % Stroke-Fast 88% Stroke-Slow 77.7%

Table C. Quality assessment of reliability, measurement error and validity for the studies of functional gait OMs (Group A). Activities Specific Confidence scale (ABC) scale. Berg Balance Scale (BBS). Barthel Index (BI). Dynamic Gait Index (DGI). Functional Ambulation Category (FAC). Functional Independence Measure (FIM). Fugl-Meyer Assessment (FMA). Four Square Step Test (FSST). Healthy participants (H). Intraclass Correlation Coefficient (ICC). meters (m). Kappa agreement (*K*). Methodological design (MD). minutes (min). Montreal Cognitive Assessment (MoCA). meter per second (m/s). Sample size (n). Postural Assessment Scale (PASS). Physiotherapist (PT). rater (R). Pearson's correlation (*r*). Spearman correlation (rho). Stroke (S). Smallest Detectable Change (SDC). Seconds (Sec). Stroke Impact Scale (SIS). Statistical Method (SM). Statistical outcomes (SO). Smallest Real Difference (SRD). Timed Up and Go test (TUG test). TUG Assessment of Biomechanical Strategies (TUG-ABS). 10-meter Walk Test (10mWT). COSMIN grading system: very good (++), adequate (+), doubtful (0), inadequate (-).

Walking test	Reliability					Measurement error			Validity				
(Author, year)	Type of reliability	n	MD	SM	SO	MD	SM	SO	Type of validity	n	MD	SM	SO
The Shuttle walk test (van Bloemendaal et al, 2012)	Test-retest	61 S	+	++	ICC $_{(2,1)}$ = 0.96	+	++	SEM= 109.m	Construct	70 S	++	++	(6-minute walk test) *r*= 0.65
EFAP validity (Wolf et al, 1999)	Inter-rater	28 S 4 R	+	+	ICC $_{(2,1)}$ = 0.98-1				Construct	28 S	++	++	10-meter walk test rho= -0.71 (BBS) rho= -0.60 (Functional reach test) rho= -0.30
mEFAP (Bear & Wolf, 2001)	Test-retest	26 S	+	+	ICC= 0.99				Construct	26 S	++	++	(BBS) rho= -0.73 (FIM) rho= -0.68
	Inter-rater	26 S	+	+	ICC= 0.99								
mEFAP (Liaw et al, 2006)	Test-retest	20 S	+	++	ICC= 0.99	+	++	SEM=2.6	Construct	40 S	++	++	(10-meter walk test) *r*=0.88 (RMI) rho= -0.67 (BI) *r*= -0.52
DGI (An et al, 2017)									Known group	57 S	++	++	DGI-8 items Cut-off score (Fallers and non-fallers) ≤16.5 AUC= 0.78, CI= 0.67–0.90 DGI-4 items Cut-off score (Fallers and non-fallers) ≤9.5 AUC= 0.77, CI= 0.65–0.89
DGI (Jonsdottir-	Test-retest	25 S 2 PTs	+	++	ICC $_{(2,1)}$ = 0.96	+	+	SEM= 0.97	Construct	25 S	++	++	(BBS) rho= 0.83 (ABC scale) rho= 0.68

Cattaneo et al, 2007)	Inter-rater		+	++	ICC $_{(2,1)}$ = 0.96	+	+	SEM= 0.94					(Timed walking test) rho= -0.73 (TUG test) rho= -0.770
DGI (Vistamehr et al, 2016)									Construct	19 S	++	++	(BBS) rho = 0.64 (MoS) rho = -0.55
Modified DGI (mDGI) (Matsuda et al, 2014)	Test-retest	239 S	0	+	α = 0.97	0	++	SDC $_{95\%}$ = 7.4	Known group	239 S 140 VD 140 H	++	0	Correlation between stroke vs healthy and VD participants. Usual pace time *r*= 0.966 Change pace time *r*= 0.946
FGA (Thieme et al, 2009)	Intra-rater	28 S 3 PT	0	++	ICC $_{(2,1)}$ = 0.97				Construct	28 S	++	++	(FAC) rho= 0.83 (Gait speed) rho= 0.82 (BBS) rho= 0.93 (RMI) rho= 0.85 (BI)rho= 0.71
	Inter-rater		0	++	ICC $_{(2,1)}$ = 0.94								
FGA (Lin et al, 2010)	Test-retest	48 S	+	++	ICC= 0.92	0	++	SDC= 4.2 points	Construct	45 S	++	++	(10mWT) rho= 0.66 (PASS) rho= 0.83
FGA (Van Bloemendaal et al, 2019)	Test-retest	52 S 3PT	+	++	ICC $_{(2,1)}$ = 0.90	0	++	SEM= 2.1 points SDC= 5.7 points	Construct	52 S	++	++	(10mWTcomfort speed) rho= 0.80 (10mWT max. speed) rho= 0.75 (BBS)rho= 0.83 (6min WT) rho= 0.78 (SIS) rho= 0.61
	Intra-rater		0	++	ICC $_{(3,1)}$ = 0.99								
	Inter-rater		+	++	ICC $_{(2,1)}$ = 0.93								

Table D. Quality assessment of reliability, measurement error and validity for the studies of functional gait OMs (Group B). Alpha coefficient (α). Activities Specific Confidence (ABC) scale. Area Under the Curve (AUC). Berg Balance Scale (BBS). Barthel Index (BI). Confidence Interval (CI). Dynamic Gait Index (DGI). Emory Functional Ambulation Profile (EFAP). Functional Ambulation Category (FAC). Functional Independence Measure (FIM). Healthy participants (H). Intraclass Correlation Coefficient (ICC). Kappa agreement (*K*). Methodological design (MD). modified Dynamic Gait Index (mDGI). modified Emory Functional Ambulation Profile (mEFAP). minutes (min). Montreal Cognitive Assessment (MoCA). Margins of stability (MoS). Sample size (n). Postural Assessment Scale (PASS). Physiotherapist (PT). rater (R). Pearson's correlation (*r*). Spearman correlation (rho). Rivermead Mobility Index (RMI). Stroke (S). Smallest Detectable

Change (SDC). Standard Error of Measurement (SEM). Statistical Method (SM). Statistical outcomes (SO). Stroke Impact Scale (SIS). Standard Response Mean (SRM). Timed Up and Go test (TUG test). TUG Assessment of Biomechanical Strategies (TUG-ABS). Vestibular Disorder (VD). 10-meter Walk Test (10Mwt). COSMIN grading system: very good (++), adequate (+), doubtful (0), inadequate (-).

Walking test	**Responsiveness**				
(Author, year)	Approach	n	MD	SM	SO
TUG test (Alghadir et al, 2018)	Construct	56 S	-	++	ES=0.38 SRM=0.53
TUG test (Persson et al, 2014)	Construct	91 S	+	++	Correlation of TUG test with age p= 0.018 Correlation of TUG test with time after stroke p= 0.085
mEFAP (Liaw et al, 2006)	Construct	40 S	+	+	SRM between admission and discharge was 1:1. The change in mEFAP was paired *t* =6.8.
DGI, DGI-4, FGA (Lin et al, 2010)	Construct	45 S	++	++	5 months after therapy FGA floor effect 0.0%, ceiling effect 5.7% DGI floor effect 0.0%, ceiling effect 11.7%
	Construct	35 S	0	++	5 months after therapy ES = 0.62, Wilcoxon Z= 3.0* *P<0.01

Table E. Quality assessment of responsiveness for studies of functional gait OMs (Group A &B). Dynamic Gait Index (DGI). Effect size (ES). Functional Gait Assessment (FGA). modified Emory Functional Ambulation Profile (mEFAP). Methodological Design (MD). sample size (n). Stroke (S). Statistical Method (SM). Statistical outcomes (SO). Standard Response Mean (SRM). Timed Up and Go test (TUG test). COSMIN grading system: very good (++), adequate (+), doubtful (0), inadequate (-).

Dual task walking test	**Test-retest Reliability**				**Measurement error**			**Validity**				
(Author, year)	n	MD	SM	SO	MD	SM	SO	Type of validity	n	MD	SM	SO
Single task condition - self-selected speed (SSP) - maximum speed (MSP) - backward walking (BW) - obstacle crossing (OCR) - TUG test DTWT with a cognitive/manual task - verbal fluency (VF) -serial subtractions (SS) - carrying a cup (CC) (Yang et al, 2016)	46 S	+	+	Walking time: Single task condition ICC $_{(2,1)}$ (SSP)= 0.80 ICC $_{(2,1)}$ (MSP)= 0.95 ICC $_{(2,1)}$ (BW)= 0.86 ICC $_{(2,1)}$ (OCR)= 0.88 ICC $_{(2,1)}$ (TUG)= 0.89 Dual task condition (a walking test+ VF) ICC $_{(2,1)}$ (SSP)= 0.83 ICC $_{(2,1)}$ (MSP)= 0.81 ICC $_{(2,1)}$ (BW)= 0.87 ICC $_{(2,1)}$ (OCR)= 0.88 ICC $_{(2,1)}$ (TUG)= 0.88 Dual task condition (a walking test+ SS) ICC $_{(2,1)}$ (SSP)= 0.78 ICC $_{(2,1)}$ (MSP)= 0.85 ICC $_{(2,1)}$ (BW)= 0.93 ICC $_{(2,1)}$ (OCR)= 0.70 ICC $_{(2,1)}$ (TUG)= 0.76 Dual task condition (a walking test+ CC) ICC $_{(2,1)}$ (SSP)= 0.80 ICC $_{(2,1)}$ (MSP)= 0.88 ICC $_{(2,1)}$ (OCR)= 0.81	+	++	Walking time: Single task condition SEM (SSP)= 1.6 SEM (MSP)= 7.6 SEM (BW)= 6 SEM (OCR)= 1.8 SEM (TUG)= 1.5 Dual task condition (a walking test+ VF) SEM (SSP)= 1.8 SEM (MSP)= 1.9 SEM (BW)= 10.1 SEM (OCR)= 2.1 SEM (TUG)= 1.9 Dual task condition (a walking test+ SS) SEM (SSP)= 2.3 SEM (MSP)= 1.7 SEM (BW)= 6.9 SEM (OCR)= 3.9 SEM (TUG)= 2.7 Dual task condition (a walking test+ CC) SEM (SSP)= 2.4 SEM (MSP)= 1.7 SEM (OCR)= 3	Construct	88 S	+	++	SSP + VF walking time TUG+ VF r= 0.93 CRR TUG+ VF r= 0.46 SSP + SS walking time TUG+ SS r= 0. 93 CRR TUG+ SS r= 0.65 SSP + CC walking time TUG+ CC r= 0.90 MS + VF walking time TUG+ VF r= 0.92 CRR TUG+ VF r= 0.53 MS + SS walking time TUG+ SS r= 0.92 CRR TUG+ SS r= 0.63

				ICC $_{(2,1)}$ (TUG)= 0.86 CRR: Single task condition* (VF) ICC $_{(2,1)}$ (SSP)= 0.63 ICC $_{(2,1)}$ (MSP)= 0.64 ICC $_{(2,1)}$ (BW)= 0.79 ICC $_{(2,1)}$ (OCR)= 0.65 ICC $_{(2,1)}$ (TUG)= 0.81 Single task condition (SS) ICC $_{(2,1)}$ (SSP)= 0.65 ICC $_{(2,1)}$ (MSP)= 0.65 ICC $_{(2,1)}$ (BW)= 0.87 ICC $_{(2,1)}$ (OCR)= 0.68 ICC $_{(2,1)}$ (TUG)= 0.73 Dual task condition (a walking test+ VF) ICC $_{(2,1)}$ (SSP)= 0.66 ICC $_{(2,1)}$ (MSP)= 0.64 ICC $_{(2,1)}$ (BW)= 0.73 ICC $_{(2,1)}$ (OCR)= 0.58 ICC $_{(2,1)}$ (TUG)= 0.75 Dual task condition (a walking test+ SS) ICC $_{(2,1)}$ (SSP)= 0.62 ICC $_{(2,1)}$ (MSP)= 0.72 ICC $_{(2,1)}$ (BW)= 0.81 ICC $_{(2,1)}$ (OCR)= 0.74 ICC $_{(2,1)}$ (TUG)= 0.59			SEM (TUG)= 2.2 CRR: Single task condition* (VF) SEM (SSP)= 0.10 SEM (MSP)= 0.14 SEM (BW)= 0.05 SEM (OCR)= 0.13 SEM (TUG)= 0.09 Single task condition (SS) SEM (SSP)= 0.12 SEM (MSP)= 0.14 SEM (BW)= 0.07 SEM (OCR)= 0.11 SEM (TUG)= 0.10 Dual task condition (a walking test+ VF) SEM (SSP)= 0.10 SEM (MSP)= 0.13 SEM (BW)= 0.07 SEM (OCR)= 0.10 SEM (TUG)= 0.08 Dual task condition (a walking test+ SS) SEM (SSP)= 0.10 SEM (MSP)= 0.11 SEM (BW)= 0.07 SEM (OCR)= 0.09 SEM (TUG)= 0.10					MS + CC walking time TUG+ CC r= 0.87 BW + VF walking time TUG+ VF r= 0.64 CRR TUG+ VF r= 0.56 BW + SS walking time TUG+ SS r= 0.66 CRR TUG+ SS r= 0.55 OCR + VF walking time TUG+ VF r= 0.90 CRR TUG+ VF r= 0.37 OCR + SS walking time TUG+ SS r= 0.86 CRR TUG+ SS r= 0.63 OCR + CC walking time TUG+ CC r= 0.87

				Dual task condition (a walking test+ CC) *K* (SSP)= 0.54 *K* (MSP)= 0.54 *K* (OCR)= 0.18 *K* (TUG)= 0.21				Known group	88 S (Fallers n= 20 Non-fallers n= 68)	++	++	AUC= 0.51-0.63 Cut-off scores (fallers & non fallers) were calculated for all DTWT tests.
Single task condition -Level-ground walking (LGW) -Obstacle crossing (OCR) DTWT with a cognitive task -auditory Stroop test (AST) -category naming (CN) -shopping list recall (SLR) -serial subtractions (SS) (Tsang et al, 2019)	30 S	0	++	Mobility parameters: Single task walking ICC $_{(2,1)}$ (LGW)= 0.97 ICC $_{(2,1)}$ (OCR)= 0.97 Obstacle hitting rate ICC $_{(2,1)}$ = 0.91 DTWT+AST ICC $_{(2,1)}$ (LGW)= 0.95 ICC $_{(2,1)}$ (OCR)= 0.98 Obstacle hitting rate ICC $_{(2,1)}$ = 0.97 DTWT+CN ICC $_{(2,1)}$ (LGW)= 0.95 ICC $_{(2,1)}$ (OCR)= 0.92 Obstacle hitting rate ICC $_{(2,1)}$ = 0.96 DTWT+SLR ICC $_{(2,1)}$ (LGW)= 0.96 ICC $_{(2,1)}$ (OCR)= 0.95 Obstacle hitting rate ICC $_{(2,1)}$ = 0.96 DTWT+SS ICC $_{(2,1)}$ (LGW)= 0.95	0	++	Mobility parameters: Single task walking **LGW** SEM= 2.7 **OCR** SEM= 2.6 Obstacle hitting rate SEM= 5.6 DTWT+AST SEM (LGW)= 2.8 SEM (OCR)= 1.8 Obstacle hitting rate SEM= 3 DTWT+CN SEM (LGW)= 2.5 SEM (OCR)= 2.9 Obstacle hitting rate SEM= 3.7 DTWT+SLR SEM (LGW)= 3.1 SEM (OCR)= 2.8 Obstacle hitting rate SEM= 3.5 DTWT+SS SEM (LGW)= 2.3	Construct	30 S	++	++	(CMSA) *r*= 0.47 (MoCA) *r*= 0.56

				ICC $_{(2,1)}$ (OCR)= 0.96 Obstacle hitting rate ICC $_{(2,1)}$ = 0.96 Cognitive parameters: DTWT (LGW) + AST ICC $_{(2,1)}$ (NCR)= 0.70 ICC $_{(2,1)}$ (RT)= 0.80 DTWT (OCR) + AST ICC $_{(2,1)}$ (NCR)= 0.68 ICC $_{(2,1)}$ (RT)= 0.50 Single task CN ICC $_{(2,1)}$ (NCR)= 0.80 DTWT (LGW) + CN ICC $_{(2,1)}$ (NCR)= 0.85 DTWT (OCR) + CN ICC $_{(2,1)}$ (NCR)= 0.71 Single task SLR ICC $_{(2,1)}$ (NCR)= 0.79 DTWT (LGW) + SLR ICC $_{(2,1)}$ (NCR)= 0.59 DTWT (OCR) + SLR (high) ICC $_{(2,1)}$ (NCR)= 0.71 Single task SS ICC $_{(2,1)}$ (NCR)= 0.87 DTWT (LGW) + SS ICC $_{(2,1)}$ (NCR)= 0.89 DTWT (OCR) + SS ICC $_{(2,1)}$ (NCR)= 0.87			SEM (OCR)= 1.9 Obstacle hitting rate SEM= 3.6 Cognitive parameters: DTWT (LGW) + AST SEM (NCR)= 2.6 SEM (RT)= 0.2 DTWT (OCR) + AST SEM (NCR)= 2.3 SEM (RT)= 0.3 Single task CN SEM (NCR)= 1.5 DTWT (LGW) + CN SEM (NCR)= 1.8 DTWT (OCR) + CN SEM (NCR)= 1.7 Single task SLR SEM (NCR)=0.5 DTWT (LGW) + SLR SEM (NCR)= 0.7 DTWT (OCR) + SLR (high) SEM (NCR)= 0.7 Single task SS SEM (NCR)= 2.0 DTWT (LGW) + SS SEM (NCR)= 2.1 DTWT (OCR) + SS SEM (NCR)= 1.9					
Walking and turn with auditory test	59 S	+	++	ICC $_{(3, k)}$ accuracy = 0.94								

T1:Test1. Auditory Stroop test. T2:Test2. Turning-while walking DTWT1. Dual Task walking (T1) DTWT2. Dual Task Walking (T2) (Chan & Tsang, 2017)	45 H			$ICC_{(3, k)}$ turn duration = 0.90 $ICC_{(3, k)}$ steps to turn = 0.85 $ICC_{(3, k)}$ time = 0.96 $ICC_{(3, k)}$ (DTWT1) reaction time = 0.62 $ICC_{(3, k)}$ (DTWT1) accuracy = 0.67 $ICC_{(3, k)}$ (DTWT2) duration = 0.96 $ICC_{(3, k)}$ (DTWT2) steps = 0.97 $ICC_{(3, k)}$ (DTWT2) time = 0.95								

Table F. Quality assessment of reliability, measurement error and validity studies for dual task walking OMs. Auditory Stroop Test (AST). Area Under the Curve (AUC). Backward Walking (BW). Carrying a Cup (CC). Chedoke McMaster Stroke Assessment for leg and foot scores (CMSA). Category Naming (CN). Correct Response Rate (CRR). Dual Task Walking Tests (DTWT). Healthy Participants (H). Kappa agreement (*K*). Level-ground walking (LGW). Methodological Design (MD). Maximum Speed (MSP). Manual Task (MT). sample size (n). Number of Correct Responses (NCR). Obstacle Crossing (OCR). Pearson's correlation *(r)*. Reaction time (RT). Stroke survivors (S). Standard Error of Measurement (SEM). Statistical Method (SM). Shopping List Recall (SLR). Statistical Outcome (SO). Smallest Real Difference (SRD). Serial Subtraction (SS). self-selected speed (SSP). Timed Up and Go test (TUG test). Verbal Fluency (VF). COSMIN grading system: very good (++), adequate (+), doubtful (0), inadequate (-). * Single- task condition in Yang et al, 2016 for cognitive tasks was performed after the dual-tasks, participants were giving a time for the cognitive tasks similar to the time spent in the dual-task. Therefore, for cognitive tasks in single condition, there were 5 tests results matched to the results from the dual tasks with different motor task. A specific procedure was followed to prevent learning effect in the cognitive tasks.

Appendix 3. A screening questionnaire for eligibility

Do you have any cardiac or pulmonary condition which is not controlled?	Yes/no	
Do you have any eye problems?	Yes/no	
Did you have any recent surgery or fracture?	Yes/no	
Do you have recent tumour or cancer?	Yes/no	
Do you have inner ear problems?	Yes/no	
Can you walk for 6-meter with or without cane?	Yes/no	
If English is not your first language, will you be able to understand and follow commands?	Yes/no	

Appendix 4. The Montreal Cognitive Assessment

MEMORY		FACE	VELVET	CHURCH	DAISY	RED	POINTS
Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.	1st trial						
	2nd trial						No points

ATTENTION		POINTS
Read list of digits (1 digit/sec)	Subject has to repeat them in the forward order ☐ 2 1 8 5 4 Subject has to repeat them in the backward order ☐ 7 4 2	___/2
Read list of letters. The subject must tap with their hand at each letter A. No points if ≥ 2 errors	☐ FBACMNAAJKLBAFAKDEAAAJAMOFAAB	___/1
Serial 7 subtraction starting at 100	☐ 93 ☐ 86 ☐ 79 ☐ 72 ☐ 65 4 or 5 correct subtractions: **3** pts, 2 or 3 correct: **2** pts, 1 correct: **1** pt 0 correct: **0** pt	___/3

LANGUAGE	POINTS
Repeat: I only know that John is the one to help today. ☐ The cat always hid under the couch when dogs were in the room. ☐	___/2
Fluency / Name maximum number of words in one minute that begin with the letter F ☐ ______ (N ≥ 11 words)	___/1

ABSTRACTION	POINTS
Similarity between e.g. banana – orange = fruit ☐ train – bicycle ☐ watch – ruler	___/2

DELAYED RECALL		FACE	VELVET	CHURCH	DAISY	RED		POINTS
	Has to recall words **WITH NO CLUE**	☐	☐	☐	☐	☐	Points for UNCUED recall only	___/5
Optional	Category cue							
	Multiple choice cue							

ORIENTATION		POINTS
	☐ Date ☐ Month ☐ Year ☐ Day ☐ Place ☐ City	___/6

 www.mocatet.org Normal ≥ 26 / 30

TOTAL ___/30
Add 1 point if ≤ 12 yr edu

Administered by: ______________________________

Appendix 5. The Motricity Index

Overview: The Motricity Index can be used to assess the motor impairment in a patient who has had a stroke.

Tests for Each Leg:

(1) **ankle dorsiflexion with foot in a plantar flexed position**

- 14 points are given if there is less than a full range of dorsiflexion
- 19 points are given for full dorsiflexion, yet it can be easily pushed down
- 25 points are given if the ankle is fully dorsiflexed against resistance
- 33 points are given if the ankle is fully dorsiflexed normally (against maximum resistance)

(2) **knee extension with the foot unsupported and the knee at 90°**

- 14 points are given for less than 50% of full extension
- 19 points are given for full extension, yet it can be easily pushed down
- 25 points are given if the knee is fully extended against resistance
- 33 points are given if the knee is fully extended normally (against maximum resistance)

(3) **hip flexion with the hip bent at 90° moving the knee towards the chin**

- 14 points are given if there is less than a full range of passive motion
- 19 points are given if the hip is fully flexed yet it can be easily pushed down
- 25 points are given if the hip is fully flexed against resistance
- 33 points are given if the hip is fully flexed normally (against maximum resistance)

Total score ___________________________/100

MRC Grade	MRC Score	Points for all Tests
no movement	0	0
palpable flicker but no movement	1	9
movement but not against gravity	2	14
movement against gravity	3	19
movement against resistance	4	25
normal	5	33

Lower limb score for each side = SUM (points for the 3 lower limb tests) + 1

Interpretation:

- minimum score: 0
- maximum score: 100

Appendix 6. The physical activity scale for persons with physical disabilities

PHYSICAL ACTIVITY SCALE FOR PERSONS WITH PHYSICAL DISABILITIES

Instructions: This questionnaire is about your current level of physical activity and exercise. Please remember there are no right or wrong answers. We simply need to assess your current level of activity.

Leisure Time Activity

1. During the past 7 days how often did you engage in stationary activities such as reading, watching TV, computer games, or doing handcrafts?
   1. Never (Go to question #2)
   2. Seldom (l-2d)
   3. Sometimes (3—4d)
   4. Often (5-7d)

   What were these activities?

   On average, how many hours per day did you spend in these stationary activities?
   1. Less than 1hr
   2. 1 but less than 2hr
   3. 2—4hr
   4. More than 4hr
2. During the past 7 days, how often did you walk, wheel, push outside your home. For example, getting to work or class, walking the dog shopping, or other errands?
   1. Never (Go to question #3)
   2. Seldom (l-2d)
   3. Sometimes (3^4d)
   4. Often (5-7d)

   On average, how many hours per day did you spend wheeling or pushing outside your home?
   1. Less than 1hr
   2. 1 but less than 2hr
   3. 2—4hr
   4. More than 4hr
3. During the past 7 days, how often did you engage in light sport or recreational activities such as bowling, golf with a cart, hunting or fishing, darts, billiards or pool, therapeutic

   On average, how many hours per day did you spend in these light sport or recreational activities?
   1. Less than 1hr
   2. 1 but less than 2hr
   3. 2-4hr
   4. More than 4hr
4. During the past 7 days, how often did you engage in moderate sport and recreational activities such as doubles tennis, softball, golf without a cart, ballroom dancing, wheeling or pushing for pleasure or other similar activities?
   1. Never (Go to question #5)
   2. Seldom (l-2d)
   3. Sometimes (3-4d)
   4. Often (5-7d)

   What were these activities?

   On average, how many hours per day did you spend in these moderate sport and recreational activities?
   1. Less than 1hr
   2. 1 but less than 2hr
   3. 2—4hr
   4. More than 4hr
5. During the past 7 days, how often did you engage in strenuous sport and recreational activities such as jogging, wheelchair racing (training), off-road pushing, swimming, aerobic dance, arm cranking, cycling (hand or leg), singles tennis, rugby, basketball, walking with crutches and braces, or other similar activities
   1. Never (Go to question #6)
   2. Seldom (1—2d)
   3. Sometimes (3-4d)
   4. Often (5—7d)

   What were these activities?

   On average, how many hours per day did you spend in these strenuous sport or recreational activities?
   1. Less than 1hr
   2. 1 but less than 2hr
   3. 2-4hr
   4. More than 4hr

Household Activity

7. During the past 7 days, how often have you done any light housework dishes?
   1. Never (Go to question #8)
   2. Seldom (1—2d)
   3. Sometimes (3-4d)
   4. Often (5—7d)

9. During the past 7 days, how often you done home repairs
   like carpentry, painting, furniture refinishing, electrical
   work, etc?
   1. Never (Go to question #10)
   2. Seldom (l-2d)
   3. Sometimes (3—4d)
   4. Often (5-7d)

   On average, how many hours per day did you spend doing home repairs?
   1. Less than 1hr
   2. 1 but less than 2hr
   3. 2—4hr
   4. More than 4hr

10. During the past 7 days how often have you done lawn work or yard care including mowing, leaf or snow removal, tree or bush trimming, or wood chopping, etc?
    1. Never (Go to question #11)
    2. Seldom (l-2d)
    3. Sometimes (3—4d)
    4. Often (5-7d)

    On average, how many hours per day did you spend doing lawn work?
    1. Less than 1hr
    2. 1 but less than 2hr
    3. 2—4hr
    4. More than 4hr

11. During the past 7 days, how often have you done outdoor gardening?
    1. Never (Go to question #12)
    2. Seldom (l-2d)

3. Sometimes (3—4d)
4. Often (5—7d)

On average, how many hours per day did you spend doing heavy housework or chores?
1. Less than 1hr
2. 1 but less than 2hr
3. 2-4hr
4. More than 4hr

3. Sometimes (3-4d)
4. Often (5-7d)

On average, how many hours per day did you spend doing outdoor gardening?
1. Less than 1hr
2. 1 but less than 2 hr
3. 2—4hr
4. More than 4hr

12. During the past 7 days, how often did you care for another person, such as children, a dependent spouse, or another adult?
    1. Never (Go to question #13)
    2. Seldom (l-2d)
    3. Sometimes (3-4d)
    4. Often (5-7d)

    On average, how many hours per day did you spend caring for another person?
    1. Less than 1hr
    2. 1 but less than 2hr
    3. 2-4hr
    4. More than 4hr

Work-Related Activity

13. During the past 7 days, how often did you work for pay or as a volunteer? (Exclude work that mainly involved sitting
    with slight arm movement such as light office work, computer work, light assembly line work, driving bus or van, etc.)
    1. Never (Go to END)
    2. Seldom (l-2d)
    3. Sometimes (3^1d)

Appendix 7. The Illness Perception Questionnaire-Revised

Participant Number: ___________ Date: ______________

YOUR VIEWS ABOUT YOUR ILLNESS
Listed below are a number of symptoms that you may or may not have experienced since your illness. Please indicate by circling *Yes* or *No*, whether you have experienced any of these symptoms since your illness, and whether you believe that these symptoms are related to your illness.

	I have experienced this symptom *since my illness*			This symptom is *related to my illness*	
Pain	Yes	No	________________	Yes	No
Sore Throat	Yes	No	________________	Yes	No
Feeling sick	Yes	No	________________	Yes	No
Breathlessness	Yes	No	________________	Yes	No
Weight Loss	Yes	No	________________	Yes	No
Fatigue	Yes	No	________________	Yes	No
Stiff Joints	Yes	No	________________	Yes	No
Sore Eyes	Yes	No	________________	Yes	No
Wheeziness	Yes	No	________________	Yes	No
Headaches	Yes	No	________________	Yes	No
Upset Stomach	Yes	No	________________	Yes	No
Sleep Difficulties	Yes	No	________________	Yes	No
Dizziness	Yes	No	________________	Yes	No
Loss of Strength	Yes	No	________________	Yes	No
Feeling forgetful	Yes	No	________________	Yes	No
What I'm like as a person has changed	Yes	No	________________	Yes	No
Clumsiness	Yes	No	________________	Yes	No
Difficulty writing	Yes	No	________________	Yes	No
Getting upset or weepy	Yes	No	________________	Yes	No
Difficulty speaking	Yes	No	________________	Yes	No
Tingling or numbness	Yes	No	________________	Yes	No
Weakness or paralysis in arm or leg	Yes	No	________________	Yes	No

CAUSES OF MY ILLNESS

We are interested in what you consider may have been the cause of your illness. As people are very different, there is no correct answer for this question. We are most interested in your own views about the factors that caused your illness rather than what others including doctors or family may have suggested to you. Below is a list of possible causes for your illness. Please indicate how much you agree or disagree that they were causes for you by ticking the appropriate box.

	POSSIBLE CAUSES	STRONGLY DISAGREE	DISAGREE	NEITHER AGREE NOR DISAGREE	AGREE	STRONGLY AGREE
C1	Stress or worry					
C2	Hereditary - it runs in my family					
C3	A Germ or virus					
C4	Diet or eating habits					
C5	Chance or bad luck					
C6	Poor medical care in my past					
C7	Pollution in the environment					
C8	My own behaviour					
C9	My mental attitude e.g. thinking about life negatively					
C10	Family problems or worries caused my illness					
C11	Overwork					
C12	My emotional state e.g. feeling down, lonely, anxious, empty					
C13	Ageing					
C14	Alcohol					
C15	Smoking					
C16	Accident or injury					
C17	My personality					
C18	Altered immunity					
C19	High cholesterol					
	POSSIBLE CAUSES	STRONGLY DISAGREE	DISAGREE	NEITHER AGREE NOR DISAGREE	AGREE	STRONGLY AGREE
C20	Blood pressure (hypertension)					

C21	Diabetes					
C22	Heart disease					
C23	Not taking enough exercise					
C24	Sudden emotional shocks					
C25	Cold					
C26	Liver disease					
C27	Heat exposure					
C28	Seizures					
C29	Getting worked up emotionally					

We are interested in your own personal views of how you now see your current illness.
Please indicate how much you agree or disagree with the following statements about your illness by ticking the appropriate box.

	VIEWS ABOUT YOUR ILLNESS	STRONGLY DISAGREE	DISAGREE	NEITHER AGREE NOR DISAGREE	AGREE	STRONGLY AGREE
IP1	Timeline The effects of my stroke will last a short time.					
IP2	My stroke is likely to be permanent rather than temporary					
IP3	The effects of my stroke will last for a long time.					
IP4	My stroke will pass quickly.					
IP5	I expect to have these symptoms for the rest of my life.					
IP6	My stroke will improve in time.					
IP7	Timeline cyclical The symptoms of my condition change a great deal from day to day.					
	VIEWS ABOUT YOUR ILLNESS	STRONGLY DISAGREE	DISAGREE	NEITHER AGREE NOR DISAGREE	AGREE	STRONGLY AGREE
IP8	My symptoms come and go in cycles.					
IP9	My condition is very unpredictable.					
IP10	I go through cycles in which my condition gets better and worse.					
IP11	Consequences My illness is a serious condition					

IP12	My stroke has major consequences on my life					
IP13	My stoke does not have much effect on my life					
IP14	My stroke strongly affects the way others see me					
IP15	My stroke has serious financial consequences					
IP16	My stroke causes difficulties for those who are close to me					
IP17	Since my stroke I fear becoming a burden on others.					
IP18	My stroke has badly affected my relationship with my family.					
IP19	My stroke has strongly affected how I see myself.					
IP20	Emotional problems since my stroke are affecting my life.					
IP21	Memory problems since my stroke are affecting my life.					
IP22	Personal control There is a lot which I can do to control my symptoms					
IP23	What I do can determine whether my stroke gets better or worse					
IP24	The course of my recovery depends on me					
IP25	Nothing I do will affect my condition					
IP26	My actions will have no effect on the outcome of my illness					
	VIEWS ABOUT YOUR ILLNESS	STRONGLY DISAGREE	DISAGREE	NEITHER AGREE NOR DISAGREE	AGREE	STRONGLY AGREE
IP27	There is nothing I can do to prevent another stroke occurring					
IP28	I need to avoid doing too much as this may cause another stroke.					
IP29	Treatment control There is very little that can be done to improve my stroke					
IP30	My treatment will help me to recover					
IP31	There is nothing which can help my condition					

IP32	Illness coherence The symptoms of my condition are puzzling to me					
IP33	My stroke is a mystery to me					
IP34	I don't understand my stroke					
IP35	My condition doesn't make any sense to me					
IP36	I have a clear picture or understanding of my condition					
IP37	Emotional representation I get depressed when I think about my illness					
IP38	When I think about my illness, I get upset					
IP39	My illness makes me feel angry					
IP40	My illness does not worry me					
IP41	Having this illness makes me feel anxious					
IP42	My illness makes me feel afraid					
IP43	I get embarrassed by the way I am since my stroke.					
IP44	My stroke is very worrying for those closest to me.					
IP45	Those closest to me get very distressed about my stroke.					

Appendix 8. The Situational Vertigo Questionnaire

Vertigo is the medical term used for symptoms which patients often describe as feelings of unusual disorientation, dizziness, giddiness, light headedness or unsteadiness. Please ring a number to indicate the degree to which each of the situations listed below causes feelings of vertigo or makes your vertigo worse. If you have never been in one of the situations, then for that item ring "N.T." for "Not Tried".

The categories are:

0	1	2	3	4	N.T.
Not at all	Very slightly	Somewhat	Quite a lot	Very much	Not tried

Riding as a passenger in a car on straight, flat roads	0	1	2	3	4	N.T.
Riding as a passenger in a car on winding or bumpy roads	0	1	2	3	4	N.T.
Walking down a supermarket aisle	0	1	2	3	4	N.T.
Standing in a lift while it stops	0	1	2	3	4	N.T.
Standing in a lift while it moves at a steady speed	0	1	2	3	4	N.T.
Riding in a car at a steady speed	0	1	2	3	4	N.T.
Starting or stopping in a car	0	1	2	3	4	N.T.
Standing in the middle of a wide-open space (e.g. large field or square)	0	1	2	3	4	N.T.
Sitting on a bus	0	1	2	3	4	N.T.
Standing on a bus	0	1	2	3	4	N.T.
Heights	0	1	2	3	4	N.T.
Watching moving scenes on the T.V. or at the cinema	0	1	2	3	4	N.T.
Travelling on escalators	0	1	2	3	4	N.T.
Looking at striped or moving surface (e.g. curtains, Venetian blinds, flowing water)	0	1	2	3	4	N.T.
Looking at a scrolling computer screen or microfiche	0	1	2	3	4	N.T.
Going through a tunnel looking at the lights on the side	0	1	2	3	4	N.T.
Going through a tunnel looking at the light at the end	0	1	2	3	4	N.T.
Driving over the brow of a hill, around bends, or in wide open spaces	0	1	2	3	4	N.T.
Watching moving traffic or trains (e.g. trying to cross the street, or at the station)	0	1	2	3	4	N.T.

Scoring= total sum/19-number not tried

Appendix 9. Mini-Balance Evaluation Test (Mini-BESTest)

Participant number____ ***SUB SCORE:*** **/6**

1. SIT TO STAND

Instruction: *"Cross your arms across your chest. Try not to use your hands unless you must. Do not let your legs lean against the back of the chair when you stand. Please stand up now."*

(2) Normal: Comes to stand without use of hands and stabilizes independently.
(1) Moderate: Comes to stand WITH use of hands on first attempt.
(0) Severe: Unable to stand up from chair without assistance, OR needs several attempts with use of hands.

2. RISE TO TOES

Instruction: *"Place your feet shoulder width apart. Place your hands on your hips. Try to rise as high as you can onto your toes. I will count out loud to 3 seconds. Try to hold this pose for at least 3 seconds. Look straight ahead. Rise now."*

(2) Normal: Stable for 3 s with maximum height.
(1) Moderate: Heels up, but not full range (smaller than when holding hands), OR noticeable instability for 3 s.
(0) Severe: $\leq$ 3 s.

3. STAND ON ONE LEG

Instruction: "Look straight ahead. Keep your hands on your hips. Lift your leg off of the ground behind you without touching or resting your raised leg upon your other standing leg. Stay standing on one leg as long as you can. Look straight ahead. Lift now."

Left: *Time in Seconds Trial 1:_____Trial 2:_____*	***Right:*** *Time in Seconds Trial 1:_____Trial 2:_____*
(2) Normal: 20 s.	(2) Normal: 20 s.
(1) Moderate: < 20 s.	(1) Moderate: < 20 s.
(0) Severe: Unable.	(0) Severe: Unable

To score each side separately use the trial with the longest time.
To calculate the sub-score and total score use the side [left or right] with the lowest numerical score [i.e. the worse side].

REACTIVE POSTURAL CONTROL____ ***SUB SCORE:*** **/6**

4. COMPENSATORY STEPPING CORRECTION- FORWARD

Instruction: "Stand with your feet shoulder width apart, arms at your sides. Lean forward against my hands beyond your forward limits. When I let go, do whatever is necessary, including taking a step, to avoid a fall."

(2) Normal: Recovers independently with a single, large step (second realignment step is allowed).
(1) Moderate: More than one step used to recover equilibrium.
(0) Severe: No step, OR would fall if not caught, OR falls spontaneously.

5. COMPENSATORY STEPPING CORRECTION- BACKWARD

Instruction: "Stand with your feet shoulder width apart, arms at your sides. Lean backward against my hands beyond your backward limits. When I let go, do whatever is necessary, including taking a step, to avoid a fall."

(2) Normal: Recovers independently with a single, large step.
(1) Moderate: More than one step used to recover equilibrium.
(0) Severe: No step, OR would fall if not caught, OR falls spontaneously.

6. COMPENSATORY STEPPING CORRECTION- LATERAL

Instruction: "Stand with your feet together, arms down at your sides. Lean into my hand beyond your sideways limit. When I let go, do whatever is necessary, including taking a step, to avoid a fall."

Left	*Right*
(2) Normal: Recovers independently with 1 step (crossover or lateral OK).	(2) Normal: Recovers independently with 1 step (crossover or lateral OK).
(1) Moderate: Several steps to recover equilibrium.	(1) Moderate: Several steps to recover equilibrium.
(0) Severe: Falls, or cannot step.	(0) Severe: Falls, or cannot step.

Use the side with the lowest score to calculate sub-score and total score.

SENSORY ORIENTATION **SUB SCORE:** ______ **/ 6**

7. STANCE (FEET TOGETHER); EYES OPEN, FIRM SURFACE

Instruction: "Place your hands on your hips. Place your feet together until almost touching. Look straight ahead. Be as stable and still as possible, until I say stop." *Time in seconds:*________

(2) Normal: 30 s.
(1) Moderate: < 30 s.
(0) Severe: Unable.

8. STANCE (FEET TOGETHER); EYES CLOSED, FOAM SURFACE

Instruction: "Step onto the foam. Place your hands on your hips. Place your feet together until almost touching. Be as stable and still as possible, until I say stop. I will start timing when you close your eyes." *Time in seconds:*________

(2) Normal: 30 s.
(1) Moderate: < 30 s.
(0) Severe: Unable.

9. INCLINE- EYES CLOSED

Instruction: "Step onto the incline ramp. Please stand on the incline ramp with your toes toward the top. Place your feet shoulder width apart and have your arms down at your sides. I will start timing when you close your eyes."
*Time in seconds:*________

(2) Normal: Stands independently 30 s and aligns with gravity.
(1) Moderate: Stands independently <30 s OR aligns with surface.
(0) Severe: Unable.

DYNAMIC GAIT **SUB SCORE:** ______ **/ 10**

10. CHANGE IN GAIT SPEED

Instruction: "Begin walking at your normal speed, when I tell you 'fast', walk as fast as you can. When I say 'slow', walk very slowly."

(2) Normal: Significantly changes walking speed without imbalance.
(1) Moderate: Unable to change walking speed or signs of imbalance.
(0) Severe: Unable to achieve significant change in walking speed AND signs of imbalance.

11. WALK WITH HEAD TURNS – HORIZONTAL

Instruction: "Begin walking at your normal speed, when I say "right", turn your head and look to the right. When I say "left" turn your head and look to the left. Try to keep yourself walking in a straight line."

(2) Normal: performs head turns with no change in gait speed and good balance.
(1) Moderate: performs head turns with reduction in gait speed.
(0) Severe: performs head turns with imbalance.

12. WALK WITH PIVOT TURNS

Instruction: "Begin walking at your normal speed. When I tell you to 'turn and stop', turn as quickly as you can, face the opposite direction, and stop. After the turn, your feet should be close together."

(2) Normal: Turns with feet close FAST ($\leq$ 3 steps) with good balance.
(1) Moderate: Turns with feet close SLOW ($\geq$4 steps) with good balance.
(0) Severe: Cannot turn with feet close at any speed without imbalance.

13. STEP OVER OBSTACLES

Instruction: "Begin walking at your normal speed. When you get to the box, step over it, not around it and keep walking."

(2) Normal: Able to step over box with minimal change of gait speed and with good balance.
(1) Moderate: Steps over box but touches box OR displays cautious behavior by slowing gait.
(0) Severe: Unable to step over box OR steps around box.

14. TIMED UP & GO WITH DUAL TASK *[3 METER WALK]*

Instruction TUG: "When I say 'Go', stand up from chair, walk at your normal speed across the tape on the floor, turn around, and come back to sit in the chair."

Instruction TUG with Dual Task: "Count backwards by threes starting at ___. When I say 'Go', stand up from chair, walk at your normal speed across the tape on the floor, turn around, and come back to sit in the chair. Continue counting backwards the entire time."

TUG: _______seconds; Dual Task TUG: _______seconds

(2) Normal: No noticeable change in sitting, standing or walking while backward counting when compared to TUG without Dual Task.

(1) Moderate: Dual Task affects either counting OR walking (>10%) when compared to the TUG without Dual Task.

(0) Severe: Stops counting while walking OR stops walking while counting.

When scoring item 14, if subject's gait speed slows more than 10% between the TUG without and with a Dual Task the score should be decreased by a point.

TOTAL SCORE: **_______/28**

Mini-BESTest Instructions

Subject Conditions: Subject should be tested with flat-heeled shoes OR shoes and socks off.

Equipment: Temper® foam (also called T-foam™ 4 inches thick, medium density T41 firmness rating), chair without arm rests or wheels, incline ramp, stopwatch, a box (9" height) and a 3 meter distance measured out and marked on the floor with tape [from chair].

Scoring: The test has a maximum score of **28** points from **14 items** that are each scored from 0-2.

"0" indicates the lowest level of function and "2" the highest level of function.

If a subject must use an assistive device for an item, score that item one category lower.

If a subject requires physical assistance to perform an item, score "0" for that item.

For **Item 3** (stand on one leg) and **Item 6** (compensatory stepping-lateral) only include the score for one side (the worse score). For **Item 3** (stand on one leg) select the best time of the 2 trials [from a given side] for the score.

For **Item 14** (timed up & go with dual task) if a person's gait slows greater than 10% between the TUG without and with a dual task then the score should be decreased by a point.

Appendix 10. Functional Gait Assessment (FGA)

Functional Gait Assessment

Requirements: A marked 6-m (20-ft) walkway that is marked with a 30.48-cm (12-in) width.

_____1. GAIT LEVEL SURFACE

Instructions: *Walk at your normal speed from here to the next mark (6 m [20 ft]).*

Grading: Mark the highest category that applies.

(3) Normal—Walks 6 m (20 ft) in less than 5.5 seconds, no assistive devices, good speed, 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 less than 7 seconds but greater than 5.5 seconds, uses assistive device, slower speed, 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), slow speed, abnormal gait pattern, evidence for imbalance, or deviates 25.438.1 cm (10-15 in) outside of the 30.48-cm (12-in) walkway width. Requires more than 7 seconds to ambulate 6 m (20 ft).

(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 normal pace (for 1.5 m [5 ft]). When I tell you "go," 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 normal, 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 next mark 6 m (20 ft) away. Begin walking at your normal 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.* 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 (eg, 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, 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 (eg, 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 next mark (6m [20 ft]). Begin walking at your normal 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.*

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 (eg, 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 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 (eg, 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

Instructions: *Begin with walking at your normal pace. When I tell you, "turn and stop," turn as quickly as you can to face the opposite direction and stop.*

Grading: Mark the highest category that applies.

(3) Normal—Pivot turns safely within 3 seconds and stops quickly with no loss of balance.

(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, 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

Instructions: *Begin walking at your normal speed. When you come to the shoe 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 stacked shoe boxes taped together (22.86 cm [9 in] total height) without changing gait speed; no evidence of imbalance.

(2) Mild impairment—Is able to step over one shoe 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 shoe 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 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 4-7 steps.
(0) Severe impairment—Ambulates less than 4 steps heel to toe or cannot perform without assistance.

_____ 8. GAIT WITH EYES CLOSED

Instructions: *Walk at your normal speed from here to the next mark (6 m [20 ft]) with your eyes closed.*
Grading: Mark the highest category that applies.

(3) Normal—Walks 6m (20ft), no assistive devices, good speed, no evidence of imbalance, nor malgait pattern, deviates no more than 15.24 cm (6 in) outside 30.48-cm (12-in) walkway width. Ambulates 6 m (20 ft) in less than 7 seconds.
(2) Mild impairment—Walks 6 m (20 ft), uses assistive device, slower speed, mild gait deviations, deviates 15.24-25.4 cm (6-10 in) outside 30.48-cm (12-in) walkway width. Ambulates 6 m (20 ft) in less than 9 seconds but greater than 7 seconds.
(1) Moderate impairment—Walks 6m (20ft), 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. Requires more than 9 seconds to ambulate 6 m (20 ft).
(0) Severe impairment—Cannotwalk6m(20ft) 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 until I tell you to stop.*
Grading: Mark the highest category that applies.

(3) Normal—Walks 6m (20ft),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 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—Cannotwalk6m(20ft) without assistance, severe gait deviations or imbalance, deviatesgreaterthan38.1 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 (ie, using the rail if necessary). At the top turn around and walk down.*
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; must use rail.
(0) Severe impairment—Cannot do safely.

TOTAL SCORE: ____ MAXIMUM SCORE 30

[a] Adapted from Dynamic Gait Index.[1] Modified and reprinted with permission of authors and Lippincott Williams & Wilkins (http://lww.com).

Appendix 11. The Cambridge Neuropsychological Test Automated Battery (CANTAB tests)

	Test name	Aim of the test	Task procedure	Outcome measure and administration Time
ATTENTION AND PSYCHOMOTOR RESPONSE	Motor Screening Task	Provides a general assessment of whether sensorimotor deficits or lack of comprehension, will limit the collection of valid data from the participant.	Task format-coloured crosses are presented in different locations on the screen, one at a time. The participant must select the cross on the screen as quickly and accurately as possible.	Speed of response and the accuracy of pointing. 2 minutes
	Reaction Time	Provides assessments of motor and mental response speeds, as well as measures of movement time, reaction time, response accuracy and impulsivity.	The participant must select and hold a button at the bottom of the screen. Circles are presented above (one for the simple mode, and five for the five-choice mode.) In each case, a yellow dot will appear in one of the circles, and the participant must react as soon as possible, releasing the button at the bottom of the screen, and selecting the circle in which the dot appeared.	Reaction time and movement time for both the simple and five-choice variants. 3 minutes
	Match to sample visual search	It assesses attention and visual searching, with a speed accuracy trade-off.	The participant is shown a complex visual pattern in the middle of the screen. After a brief delay, a varying number of similar patterns are shown in a circle of boxes around the edge of the screen. Only one of these patterns matches the pattern in the centre of the screen, and the participant must indicate which it is by selecting it.	Accuracy and reaction time. 7 minutes
	Rapid Visual Information process	It assesses sustained attention	A white box is shown in the centre of the screen, inside which digits from 2 to 9 appear in a pseudo-random order, at the rate of 100 digits per minute. Participants	Latency (speed of response), probability

			are requested to detect target sequences of digits (for example, 2-4-6, 3-5-7, 4-6-8). When the participant sees the target sequence, they must respond by selecting the button in the centre of the screen as quickly as possible.	of false alarms and sensitivity. 7 minutes
MEMORY	Spatial Working Memory	Requires retention and manipulation of visuospatial information. This self-ordered test has notable executive function demands and provides a measure of strategy as well as working memory errors.	The test begins with a number of coloured squares (boxes) shown on the screen. By selecting the boxes and using a process of elimination, the participant should find one yellow 'token' in each of a number of boxes and use them to fill up an empty column on the right-hand side of the screen. The colour and position of the boxes used are changed from trial to trial to discourage the use of stereotyped search strategies.	The errors and strategy. 4 minutes.
	Paired Associates Learning	Assesses visual memory and new learning.	Boxes will be displayed on the screen and are "opened" in a randomised order. One or more of them will contain a pattern. The patterns are then displayed in the middle of the screen, one at a time and the participant must select the box in which the pattern was originally located. If the participant makes an error, the boxes are opened in sequence again to remind the participant of the locations of the patterns.	The errors, the number of trials required to locate the pattern(s) correctly, memory scores and stages completed. 8 minutes.

Appendix 12. Environmental Analysis Mobility Questionnaire

Participant Number: ___________ Date: ______________

Environmental Analysis of Mobility Questionnaire

We are interested in learning more about your walking activities in the community over the past month. In this walking activities questionnaire, I will be asking you to report about trips away from your home. The word "trip" means when you leave your home and go into the community to perform an activity, such as grocery shopping. I will be asking about questions about how often you go on trips away from your home, where you go, and what time of day you tend to travel, and the kind of obstacles you encounter, such as steps. You are free not to answer any questions you do not wish to answer.

1. When you go on a trip away from your home, how often do you go alone? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
2. When you go on a trip away from your home, how often do you avoid going out alone? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
3. When you go on a trip away from your home, what is the average number of blocks you walk? 0 = 0 – 1 block 1 = 2 – 4 blocks (1/4 mile) 2 = 5 – 9 blocks (1/2 mile) 3 = >10 blocks (1 mile)
4. When you go on a trip away from your home, how often do you purposely limit the amount you have to walk? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
5. When you go on a trip away from your home, how often do you have to cross a street at a traffic light? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
6. How often do you avoid a situation in which you have to cross a street at a traffic light? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

7. When you go on a trip away from your home, how often do you have to walk across a busy street? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
8. How often do you avoid a situation in which you have to walk across a busy street? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
9. When you go on a trip away from your home, how often do you go when it is dark? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
10. When you go on a trip away from your home, how often do you avoid going when it is dark? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
11. When you go on a trip away from your home, how often do you go when it is raining? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
12. When you go on a trip away from your home, how often do you avoid going when it is raining? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
13. When you go on a trip away from your home, how often do you go when it is snowing? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
14. When you go on a trip away from your home, how often do you avoid going when it is snowing? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
15. When you go on a trip away from your home, how often do you usually climb a single flight of stairs (that is about 10 steps)? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
16. How often do you purposely avoid a situation where you would have to climb a single flight of stairs? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

17. When you go on a trip away from your home, how often do you climb two or more flights of stairs (that is about 20 steps)? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
18. How often do you purposely avoid a situation where you would have to climb two or more flights of stairs? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
19. When you go on a trip away from your home, how often do you go up or down an escalator? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
20. How often do you purposely avoid a situation where you would have to go up or down an escalator? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
21. When you go on a trip away from your home, how often do you go up and down curbs? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
22. How often do you purposely avoid a situation where you would have to go up or down a curb? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
23. When you go on a trip away from your home, how often do you walk on uneven surfaces? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
24. How often to you purposely avoid a situation in which you would have to walk on an uneven surface? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
25. During a trip away from your home, how often do you usually carry two or more items? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
26. How often do you limit the number, or weight, of items you carry? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
27. When you go on a trip away from your home, how often do you open doors that require moderate strength?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

28. When you go on a trip away from your home, how often do you avoid opening doors that require moderate strength? (e.g. use wheelchair access button)

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

29. When you are grocery shopping, how often do you reach above shoulder height to get something?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

30. When you are grocery shopping, how often do you avoid reaching above shoulder height to get something?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

31. When you are grocery shopping, how often do you reach below your knee level?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

32. When you are grocery shopping, how often do you avoid reaching below your knee level?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

33. When you are grocery shopping, how often do you have to lean forward to reach for something?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

34. When you are grocery shopping, how often do you avoid leaning forward to reach for something?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

35. When you go on a trip away from your home, how often do you go with two or more people?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

36. When you go on a trip away from your home, how often do you walk through noisy or busy places?

0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

37. How often to you purposely avoid a situation in which you would have to walk through noisy or busy places? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
38. When you go on a trip away from your home, how often do you go to unfamiliar places? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
39. How often do you avoid going to places you are not familiar with? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
40. How often do you go to places where there are a lot of people who might bump into you? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always
41. How often do you purposely avoid a situation where there are a lot of people who might bump into you? 0 = never 1 = rarely 2 = sometimes 3 = often 4 = always

Appendix 13. Hospital Anxiety and Depression Scale

Participant Number: ___________ Date: ______________

HOSPITAL ANXIETY AND DEPRESSION SCALE

Emotions play an important part in most medical conditions. The following questions are designed to help us know about how you feel and how things have been since the onset of your condition. Read each item and underline the reply which comes closest to how you have been feeling since your symptoms began. Don't take too long over your replies; your immediate reaction to each item will probably be more accurate than a long thought out response.

1. I feel tense or "wound up": Most of the time**/** A lot of the time**/** From time to time, occasionally**/** Not at all
2. I still enjoy the things I used to enjoy: Definitely as much/ Not quite as much/ Only a little/ Hardly at all
3. I get a sort of frightened feeling as if something awful is about to happen: Very definitely and quite badly/ Yes, but not too badly/ A little, but it doesn't worry me/ Not at all
4. I can laugh and see the funny side of things: As much as I always could/ Not quite as much now/ Definitely not so much now/ Not at all
5.Worrying thoughts go through my mind: A great deal of the time/ A lot of the time/ From time to time but not too often/ only occasionally
6. I feel cheerful:

Not at all/ Not often/ Sometimes/ Most of the time
7. I can sit at ease and feel relaxed: Definitely/ Usually/ Not often/ Not at all
8. I feel as if I am slowed down: Nearly all the time/ Very often/ Sometimes/ Not at all
9. I get a sort of frightened feeling like 'butterflies' in the stomach: Not at all/ Occasionally/ Quite often/ Very often
10. I have lost interest in my appearance: Definitely/ I don't take so much care as I should/ I may not take quite as much care/ I take just as much care as ever
11. I feel restless as if I have to be on the move: Very much indeed/ Quite a lot/ Not very much/ Not at all
12. I look forward with enjoyment to things: As much as ever I did/ Rather less than I used to/ Definitely less than I use to/ Hardly at all
13. I get sudden feelings of panic: Very often indeed/ Quite often/ Not very often/ Not at all
14. I can enjoy a good book or radio or T.V. programme: Often/ Sometimes/ Not often/ Very seldom

Appendix 14. Activities-specific Balance Confidence scale

Participant Number: ___________ Date: ______________

The Activities-specific Balance Confidence (ABC) scale

For each of the following activities, please indicate your level of self-confidence by choosing a corresponding number from the following rating scale:

0% 10 20 30 40 50 60 70 80 90 100%

no confidence completely confident

"How confident are you that you will **not** lose your balance or become unsteady when you…
…walk around the house? ____%
…walk up or down stairs? ____%
…bend over and pick up a slipper from the front of a cupboard floor ____%
…reach for a small can off a shelf at eye level? ____%
…stand on your tiptoes and reach for something above your head? ____%
…stand on a chair and reach for something? ____%
…sweep the floor? ____%
…walk outside the house to a car parked in the driveway? ____%
…get into or out of a car? ____%
…walk across a parking lot to the shopping centre? ____%
…walk up or down a ramp? ____%
…walk in a crowded shopping centre where people rapidly walk past you?

____%
…are bumped into by people as you walk through the shopping Centre? ____%
… step onto or off an escalator while you are holding onto a railing? ____%
…step onto or off an escalator while holding onto parcels such that you cannot hold onto the railing? ____%
…walk outside on icy pavements? ____%

Appendix 15. Dizziness Handicap Inventory

Participant Number: ___________ Date: ______________

The Dizziness Handicap Inventory

P1. Does looking up increase your problem?	o o o	Yes Sometimes No
E2. Because of your problem, do you feel frustrated?	o o o	Yes Sometimes No
F3. Because of your problem, do you restrict your travel for business or recreation?	o o o	Yes Sometimes No
P4. Does walking down the aisle of a supermarket increase your problems?	o o o	Yes Sometimes No
F5. Because of your problem, do you have difficulty getting into or out of bed?	o o o	Yes Sometimes No
F6. Does your problem significantly restrict your participation in social activities, such as going out to dinner, going to the movies, dancing, or going to parties?	O o o	Yes Sometimes No
F7. Because of your problem, do you have difficulty reading?	o o o	Yes Sometimes No
P8. Does performing more ambitious activities such as sports, dancing, household chores (sweeping or putting dishes away) increase your problems?	o o o	Yes Sometimes No
E9. Because of your problem, are you afraid to leave your home without having without having someone accompany you?	o o o	Yes Sometimes No
E10. Because of your problem have you been embarrassed in front of others?	o o o	Yes Sometimes No
P11. Do quick movements of your head increase your problem?	o o o	Yes Sometimes No
F12. Because of your problem, do you avoid heights?	o o o	Yes Sometimes No
P13. Does turning over in bed increase your problem?	o	Yes

	o o	Sometimes No
F14. Because of your problem, is it difficult for you to do strenuous homework or yard work?	o o o	Yes Sometimes No
E15. Because of your problem, are you afraid people may think you are intoxicated?	o o o	Yes Sometimes No
F16. Because of your problem, is it difficult for you to go for a walk by yourself?	o o o	Yes Sometimes No
P17. Does walking down a sidewalk increase your problem?	o o o	Yes Sometimes No
E18.Because of your problem, is it difficult for you to concentrate	o o o	Yes Sometimes No
F19. Because of your problem, is it difficult for you to walk around your house in the dark?	o o o	Yes Sometimes No
E20. Because of your problem, are you afraid to stay home alone?	o o o	Yes Sometimes No
E21. Because of your problem, do you feel handicapped?	o o o	Yes Sometimes No
E22. Has the problem placed stress on your relationships with members of your family or friends?	o o o	Yes Sometimes No
E23. Because of your problem, are you depressed?	o o o	Yes Sometimes No
F24. Does your problem interfere with your job or household responsibilities?	o o o	Yes Sometimes No
P25. Does bending over increase your problem?	o o o	Yes Sometimes No

Appendix 16. Health-related Quality of Life (EQ-5D-5L)

MOBILITY

I have no problems in walking about
I have slight problems in walking about
I have moderate problems in walking about
I have severe problems in walking about
I am unable to walk about

SELF-CARE

I have no problems washing or dressing myself
I have slight problems washing or dressing myself
I have moderate problems washing or dressing myself
I have severe problems washing or dressing myself
I am unable to wash or dress myself

USUAL ACTIVITIES e.g. work, study, housework, family or leisure activities

I have no problems doing my usual activities
I have slight problems doing my usual activities
I have moderate problems doing my usual activities
I have severe problems doing my usual activities
I am unable to do my usual activities

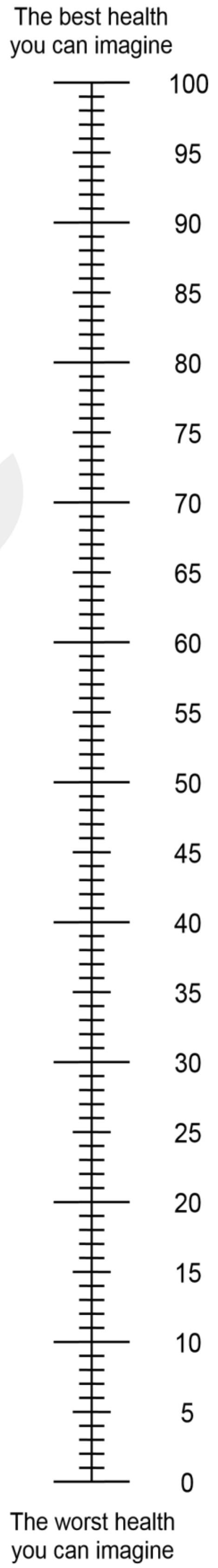
PAIN / DISCOMFORT

I have no pain or discomfort
I have slight pain or discomfort
I have moderate pain or discomfort
I have severe pain or discomfort
I have extreme pain or discomfort

ANXIETY / DEPRESSION

I am not anxious or depressed
I am slightly anxious or depressed
I am moderately anxious or depressed
I am severely anxious or depressed
I am extremely anxious or depressed

- We would like to know how good or bad your health is TODAY.
- This scale is numbered from 0 to 100.
- 100 means the <u>best</u> health you can imagine.
  0 means the <u>worst</u> health you can imagine.
- Mark an X on the scale to indicate how your health is TODAY.
- Now, please write the number you marked on the scale in the box below.



YOUR HEALTH TODAY = ☐

Appendix 17. The Pittsburgh Sleep Quality Index

Instructions:

The following questions relate to your usual sleep habits during the past month only. Your answers should indicate the most accurate reply for the majority of days and nights in the past month. Please answer all the questions.

1.During the past month, when have you usually gone to bed at night?

Usual bedtime

2.During the past month, how long (in minutes) has it usually takes you to fall asleep each night?

Number of minutes

3.During the past month, when have you usually got up in the morning?

Usual getting up time

4.During the past month, how many hours of actual sleep did you get at night? (This may be different than the number of hours you spend in bed).

Hours of sleep per night

For each of the remaining questions, check the one best response. Please answer all questions.

5.During the past month, how often have you had trouble sleeping because you……

(a) Cannot get to sleep within 30 minutes

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

(b)Wake up in the middle of the night or early morning

Not during the past month	Less than once a week	Once or twice a week	Three or more times a week

(c)Have to get up to use the bathroom

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

(d)Cannot breathe comfortably

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

(e)Cough or snore loudly

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

(f)Feel too cold

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

(g)Feel too hot

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

(h)Had bad dreams

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

(i)Have pain

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

(j)Other reason(s), please describe

How often during the past month have you had trouble sleeping because of this?

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

6.During the past month, how would you rate your sleep quality overall?

Very good
Fairly good
Fairly bad
Very bad

7.During the past month, how often have you taken medicine (prescribed or " over the counter") to help you sleep?

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

8.During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?

Not during the past month	Less than once a week	Once or twice a week	three or more times a week

9.During the past month, how much of a problem has it been for you to keep up enough enthusiasm to get things done.

No problem at all
Only a very slight problem
Somewhat of a problem
A very big problem

10.Do you have a bed partner or roommate?

No bed partner or roommate
Partner/roommate in other room
Partner in same room, but not same bed
Partner in same bed

11.How often do you feel tired during the following times during the day?

Morning:

0	1	2	3
most days	often	occasionally	never

Afternoon:

0	1	2	3
most days	often	occasionally	never

Evening:

0	1	2	3
most days	often	occasionally	never

The Epworth Sleepiness Scale

Initials:
Date:
Date of Birth:
Gender: Male/ Female (delete as appropriate)

Appendix 18. Epworth Sleepiness Scale

How likely are you to doze off or fall asleep in the following situations, in contrast to feeling just tired? This refers to your usual way of life in recent times. Even if you haven't done some of these things recently try to work out how they would have affected you.

Use the following scale to choose the **most appropriate number** for each situation:

0 = would **never** doze
1 = **slight chance** of dozing
2 = moderate chance of dozing
3 = **high chance** of dozing

It is important that you answer each question as best you can.

Situation	Chance of Dozing (0-3)
Sitting and reading	
Watching TV	
Sitting, inactive in a public place (e.g. a theatre or a meeting)	
As a passenger in a car for an hour without a break	
Lying down to rest in the afternoon when circumstances permit	
Sitting and talking to someone	
Sitting quietly after a lunch without alcohol	
In a car, while stopped for a few minutes in the traffic	

Appendix 19. The semi structured interview questions

Can you tell me why you signed up for this project?

Thinking about your balance or feeling off-balance or a fear of falling: Can you explain whether you have noticed any changes since you started the project? What would you attribute them to?

Can you describe your experience of using the HOLOBalance system?

What did you feel worked well with the system (HARDWARE)/ what parts did you like the most?

What were your least favourite parts of the system (HARDWARE)?

What sort of problems or frustrations did you experience with the exercises or games?

What were your favourite exercises / games in HOLOBalance?

Which games did you feel helped your balance the most and why?

How did any of the games specifically help with any day to day tasks? Such as walking outside? Household chores?

What would you like to see added to the whole HOLOBalance system?

What would you like to take out or change?

Would you recommend this system to any of your friends? If yes, why? If not, why?

What surprised you in the system?

How does it feel to have all your progress automatically shared with the doctor?

Appendix 20. The System Usability Scale

	1 (strongly disagree) to 5 (strongly agree)
I think that I would like to use this system frequently	
I found the system unnecessarily complex	
I thought the system was easy to use	
I think that I would need the support of technical person to be able to use this system	
I found the various functions in this system were well integrated	
I thought there was too much inconsistency in this system	
I would imagine that most people would learn to use this system very quickly	
I found the system very cumbersome to use	
I felt very confident using the system	
I needed to learn a lot of things before I could get going with this system	

Appendix 21. The User Experience Questionnaire

Attractiveness	annoying / enjoyable
	good / bad
	unlikable / pleasing
	unpleasant / pleasant
	attractive / unattractive
	friendly / unfriendly
Perspicuity	not understandable / understandable
	easy to learn / difficult to learn
	complicated / easy
	clear / confusing
Efficiency	fast / slow
	inefficient / efficient
	impractical / practical
	organized / cluttered
Dependability	unpredictable / predictable
	obstructive / supportive
	secure / not secure
	meets expectations / does not meet expectations
Stimulation	valuable / inferior
	boring / exiting
	not interesting / interesting
	motivating / demotivating
Novelty	creative / dull
	inventive / conventional
	usual / leading edge
	conservative / innovative

Appendix 22. NASA Task Load Index

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Appendix 23. World Health Organisation Disability Assessment Schedule

WHODAS 2.0

WORLD HEALTH ORGANIZATION
DISABILITY ASSESSMENT SCHEDULE 2.0

12-item version, self-administered

This questionnaire asks about difficulties due to health conditions. Health conditions include diseases or illnesses, other health problems that may be short or long lasting, injuries, mental or emotional problems, and problems with alcohol or drugs.

Think back over the past 30 days and answer these questions, thinking about how much difficulty you had doing the following activities. For each question, please circle only one response.

In the past 30 days, how much difficulty did you have in:						
S1	Standing for long periods such as 30 minutes?	None	Mild	Moderate	Severe	Extreme or cannot do
S2	Taking care of your household responsibilities?	None	Mild	Moderate	Severe	Extreme or cannot do
S3	Learning a new task, for example, learning how to get to a new place?	None	Mild	Moderate	Severe	Extreme or cannot do
S4	How much of a problem did you have joining in community activities (for example, festivities, religious or other activities) in the same way as anyone else can?	None	Mild	Moderate	Severe	Extreme or cannot do
S5	How much have you been emotionally affected by your health problems?	None	Mild	Moderate	Severe	Extreme or cannot do

Please continue to next page...

.

WHODAS 2.0

WORLD HEALTH ORGANIZATION
DISABILITY ASSESSMENT SCHEDULE 2.0

12
Self

In the past 30 days, how much difficulty did you have in:						
S6	Concentrating on doing something for ten minutes?	None	Mild	Moderate	Severe	Extreme or cannot do
S7	Walking a long distance such as a kilometre [or equivalent]?	None	Mild	Moderate	Severe	Extreme or cannot do
S8	Washing your whole body?	None	Mild	Moderate	Severe	Extreme or cannot do
S9	Getting dressed?	None	Mild	Moderate	Severe	Extreme or cannot do
S10	Dealing with people you do not know?	None	Mild	Moderate	Severe	Extreme or cannot do
S11	Maintaining a friendship?	None	Mild	Moderate	Severe	Extreme or cannot do
S12	Your day-to-day work?	None	Mild	Moderate	Severe	Extreme or cannot do

H1	Overall, in the past 30 days, how many days were these difficulties present?	***Record number of days*** ____
H2	In the past 30 days, for how many days were you totally unable to carry out your usual activities or work because of any health condition?	***Record number of days*** ____
H3	In the past 30 days, not counting the days that you were totally unable, for how many days did you cut back or reduce your usual activities or work because of any health condition?	***Record number of days*** ____

This completes the questionnaire. Thank you.

Appendix 24. The Falls Efficacy Scale International

Short FES-I

Now we would like to ask some questions about how concerned you are about the possibility of falling. Please reply thinking about how you usually do the activity. If you currently don't do the activity, please answer to show whether you think you would be concerned about falling IF you did the activity. For each of the following activities, please tick the box which is closest to your own opinion to show how concerned you are that you might fall if you did this activity.

		Not at all concerned *1*	*Somewhat concerned* *2*	*Fairly concerned* *3*	*Very concerned* *4*
1	Getting dressed or undressed	*1* ☐	*2* ☐	*3* ☐	*4* ☐
2	Taking a bath or shower	*1* ☐	*2* ☐	*3* ☐	*4* ☐
3	Getting in or out of a chair	*1* ☐	*2* ☐	*3* ☐	*4* ☐
4	Going up or down stairs	*1* ☐	*2* ☐	*3* ☐	*4* ☐
5	Reaching for something above your head or on the ground	*1* ☐	*2* ☐	*3* ☐	*4* ☐
6	Walking up or down a slope	*1* ☐	*2* ☐	*3* ☐	*4* ☐
7	Going out to a social event (e.g. religious service, family gathering or club meeting)	*1* ☐	*2* ☐	*3* ☐	*4* ☐

Appendix 25. The Rapid Assessment of Physical Activity

How physically active are you? *(Check one answer on each line)*

		Does this accurately describe you?	
1	I rarely or never do any physical activities.	Yes ☐	No ☐
2	I do some **light** or **moderate** physical activities, but not every week.	Yes ☐	No ☐
3	I do some **light** physical activity every week.	Yes ☐	No ☐
4	I do **moderate** physical activities every week, but less than 30 minutes a day or 5 days a week.	Yes ☐	No ☐
5	I do **vigorous** physical activities every week, but less than 20 minutes a day or 3 days a week.	Yes ☐	No ☐
6	I do 30 minutes or more a day of **moderate** physical activities, 5 or more days a week.	Yes ☐	No ☐
7	I do 20 minutes or more a day of **vigorous** physical activities, 3 or more days a week.	Yes ☐	No ☐

3 = Both 1 & 2

1	I do activities to increase muscle **strength**, such as lifting weights or calisthenics, once a week or more.	Yes ☐	No ☐
2	I do activities to improve **flexibility**, such as stretching or yoga, once a week or more.	Yes ☐	No ☐

Appendix 26. The Behavioural Regulation in Exercise Questionnaire

EXERCISE REGULATIONS QUESTIONNAIRE (BREQ-3)

Age: _______ years **Sex:** male female (please circle)

WHY DO YOU ENGAGE IN EXERCISE?

We are interested in the reasons underlying peoples' decisions to engage or not engage in physical exercise. Using the scale below, please indicate to what extent each of the following items is true for you. Please note that there are no right or wrong answers and no trick questions. We simply want to know how you personally feel about exercise. Your responses will be held in confidence and only used for our research purposes.

		Not true for me		Sometimes true for me		Very true for me
1	It's important to me to exercise regularly	0	1	2	3	4
2	I don't see why I should have to exercise	0	1	2	3	4
3	I exercise because it's fun	0	1	2	3	4
4	I feel guilty when I don't exercise	0	1	2	3	4
5	I exercise because it is consistent with my life goals	0	1	2	3	4
6	I exercise because other people say I should	0	1	2	3	4
7	I value the benefits of exercise	0	1	2	3	4
8	I can't see why I should bother exercising	0	1	2	3	4
9	I enjoy my exercise sessions	0	1	2	3	4
10	I feel ashamed when I miss an exercise session	0	1	2	3	4
11	I consider exercise part of my identity	0	1	2	3	4
12	I take part in exercise because my friends/family/partner say I should	0	1	2	3	4
13	I think it is important to make the effort to exercise regularly	0	1	2	3	4
14	I don't see the point in exercising	0	1	2	3	4
15	I find exercise a pleasurable activity	0	1	2	3	4
16	I feel like a failure when I haven't exercised in a while	0	1	2	3	4
17	I consider exercise a fundamental part of who I am	0	1	2	3	4
18	I exercise because others will not be pleased with me if I don't	0	1	2	3	4
19	I get restless if I don't exercise regularly	0	1	2	3	4
20	I think exercising is a waste of time	0	1	2	3	4

Appendix 27. The Ethical Approval Letter

Research Ethics Office

Franklin Wilkins Building
5.9 Waterloo Bridge Wing
Waterloo Road
London SE1 9NH
Telephone 020 7848 4020/4070/4077
rec@kcl.ac.uk

KING'S College LONDON

19 January 2022

Dear Kawthar

Reference Number: RESCM-21/22-21866

Study Title: Predictive factors for functional gait and physical activity in stroke survivors vs healthy adults.

Modification Review Outcome: Approval with provisos

Thank you for submitting a modification request for the above study. I am writing to confirm that your request has been approved with provisos, laid out in the feedback table below.

Important COVID-19 update: Please consult the latest College guidance (linked below) and ensure you have completed the risk assessment procedure prior to any data collection involving face-to-face participant interactions.

https://internal.kcl.ac.uk/innovation/research/ethics/applications/COVID-19-Update-for-Researchers

You are not required to provide evidence that these provisos have been met. However, the approval of your modification is only valid if these changes are made. You must not implement this modification until these provisos have been met.

If you have any questions regarding this application please contact the Research Ethics Office.

Kind regards

Dr Alexander Miller Tate

Research Ethics Facilitator

On behalf of

BDM Research Ethics Subcommittee

Review Reference: RESCM-21/22-21866

Feedback requiring substantial consideration

N/A

Minor feedback related to application

N/A

Research Governance & Data Protection feedback

N/A

Feedback related to recruitment documents

Consent Form

Point 7 - Please remove this point, or clarify what assessment records will be accessed for healthy participants (here and on the PIS).

Information Sheet

Page 1 of 2

- Under 'Data Handling and Confidentiality' you state 'If you withdraw from the study, we will keep the information about you that we have already obtained.' Under 'What if I change my mind about taking part' you state 'If you choose to withdraw your data from the study, we will not retain the information you have given thus far.' Please amend for consistency.

Advice and Comments (do not have to be adhered to, but may help to improve the research)

Consent Form

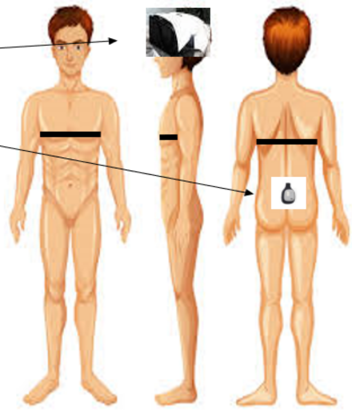
Point 2 - Please consider removing the reference to 'medical care' here, since it is likely to be irrelevant and confusing to healthy participants.

Appendix 28. The Pictorial guide for HOLOBalance group

Instructions to get ready for the HOLOBALANCE programme.

We suggest that you put **both mobile phones, disc batteries** for the insoles, and **white sensors** on charge after each exercise session (minimum 2 hours charging is required).

 +  + 



How you charged the batteries and the sensors?

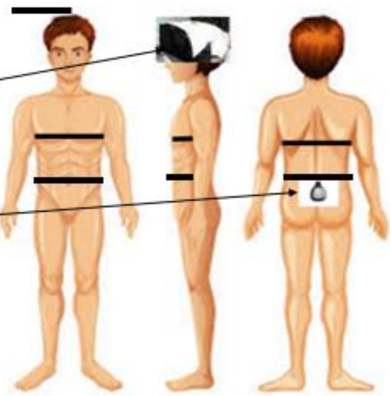
- To charge the disc batteries for the insoles, please make sure the + icon on the batteries placed within the + side in the charger.

- To charge the white sensors, please use the white cables.

Immediately prior to exercising:

A. **Back and Head sensors**

1. Remove white sensors from charge.
2. The head sensor  will be fixed to the headset, and you
can charge it while it is fixed there.
3. Place the sensor marked **'B'**  into its black rubber holder. The grey dot needs to face downward.
4. Place the belt around your waist (over clothes).



B. **Insoles**

1. Remove the disc batteries from the charger. 
2. Place one battery into each insole  
3. Place insoles into exercise shoes

c. **Other wearable devices.**

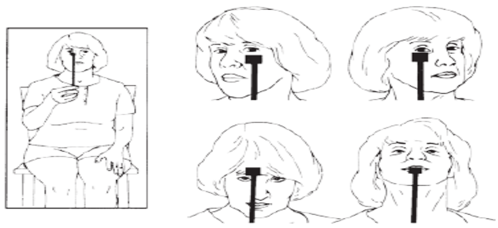
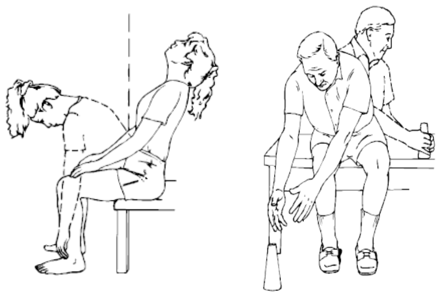
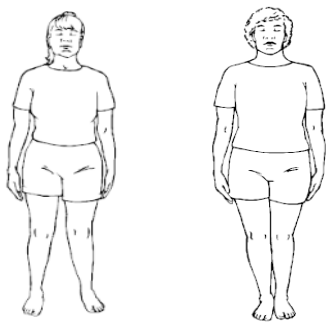
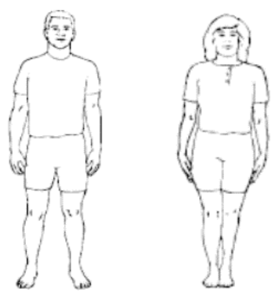
1. Prepare the POLAR heart rate monitor by moistening the smooth sensors on the chest strap. Then fasten strap to chest.

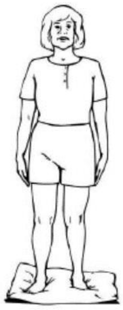
2. Fasten Fitbit to your wrist.

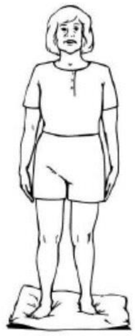
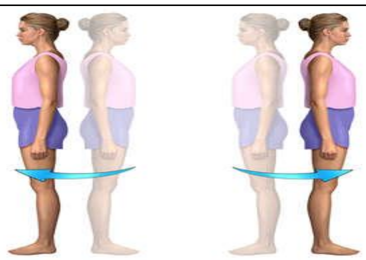
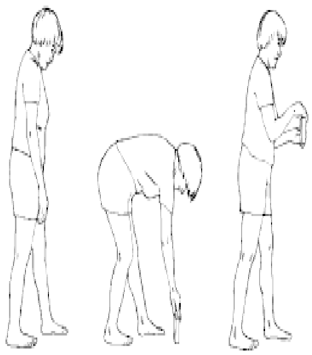
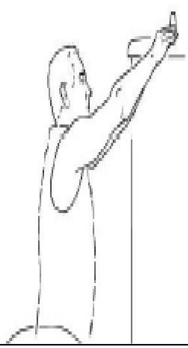
Ready to start.

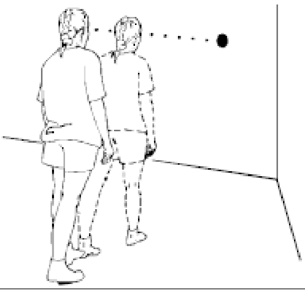
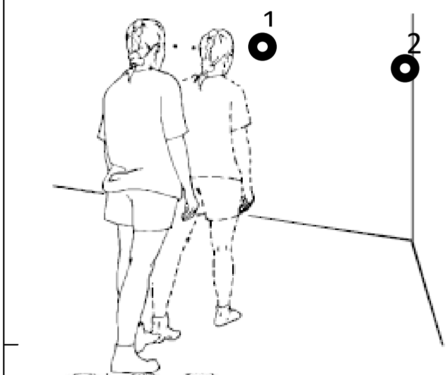
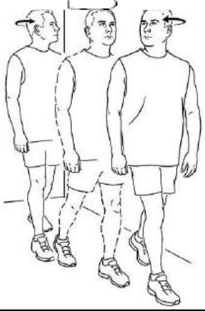
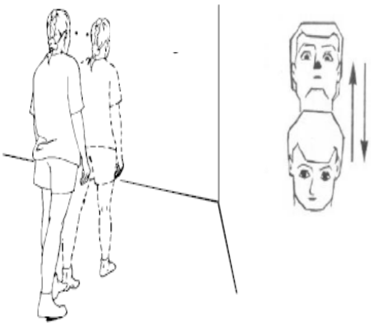
1. Make sure you are in front, but sideways onto the camera. For safety, make sure you have something firm to hold onto during exercise if needed (a table for example).
2. Turn on the PC. You will hear open the program from the PC.
3. Open the Holobalance App on the Pixel (or Samsung) phone.
4. Place the Pixel (or Samsung) phone into the headset.
   (You can keep the phone in the headset and charged while in the headset after the exercise finish).
5. The Holobalance program should now begin.

Appendix 29. The Multisensory Rehabilitation (MSR) exercises

Exercise	Instructions
	Sit in a comfortable chair. 1. Turn your head right and left while focusing your gaze on an object. Repeat ____ 2. Move your head from up to down while focusing your gaze on an object. Repeat ____
	3. From sitting, lean forward as you pick an object from the floor. 4. Take the object toward backward, 2. Take it toward your side. Repeat ____
	4. From standing, within your feet within shoulder apart, try to move your feet closer to be touched together for ________ seconds.
	5. From standing, within your feet within shoulder apart and eyes closed, try to move your feet closer to be touched together for _____ seconds while maintain your eyes closed.

	6. Stand close to a firm object, for example a firm table, then stand on a cushion with your feet within shoulder distance for ________seconds.
	7. Stand close to a firm object, for example a firm table, then stand on a cushion with your feet closed together for ____ seconds.

	8. Stand close to a firm object, for example a firm table, then stand on a cushion with your feet within shoulder distance and eyes closed for ______ seconds.
	9. Stand close to a firm object, for example a firm table, then stand on a cushion with your feet closed together and eyes closed for ______seconds.
	10. From standing, turn to each side, repeat ____
 	11. From standing, try to raise yourself up as to pick an object from floor. repeat ____

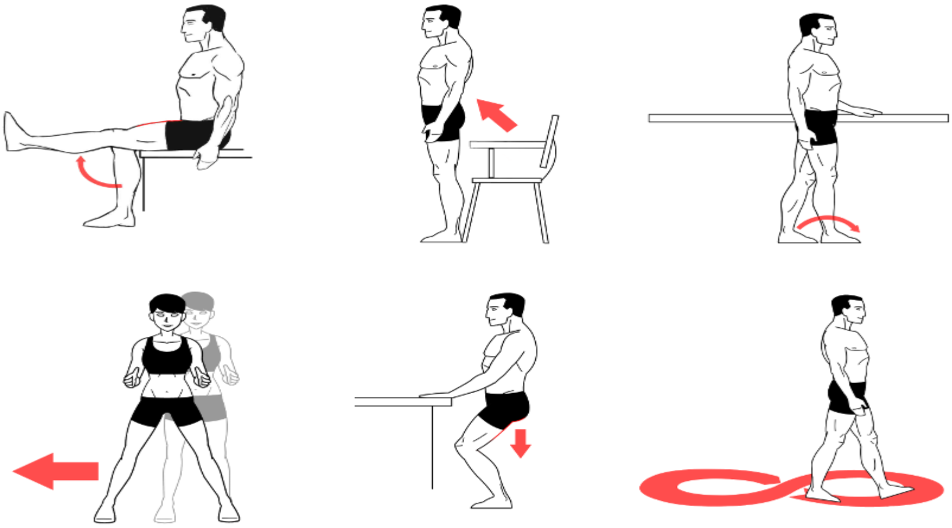
	12. Walk for 3-meter (for example) in straight line. While you are walking stay your gaze focus on one point. repeat ____
	13. Walk for 3-meter (for example) in straight line. While you are walking stay your gaze focus on two points. repeat ____
	14. Walk for 3-meter (for example) in straight line. While you are walking move your head up and down. repeat ______
	15. Walk for 3-meter (for example) in straight line. While you are walking turn your head right and left. repeat ____

Appendix 30. Home Exercise Log

Please record on the table below whether you completed your prescribed exercises for each day. Please also record how much additional activity (and the type of activity) you completed on each day.

Week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity
	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity
	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity
	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity	Exercises Completed Extra Activity

Appendix 31. Sample of the Otago exercises



Appendix 32. The Ethical Approval HOLOBalance feasibility for stroke survivors.

Research Ethics
Office

Franklin Wilkins Building
5.9 Waterloo Bridge Wing
Waterloo Road
London SE1 9NH
Telephone 020 7848 4020/4070/4077
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KING'S College LONDON

Kawthar Ajaj

18/02/2022

Dear Kawthar

Reference Number: HR/DP-21/22-26295
Study Title: Balance training with holographic exergames for stroke survivors: a feasibility study.

Review Outcome: Approval with Provisos

Ethical Clearance

Thank you for submitting your application for the above project. I am pleased to inform you that your application has now been approved with the provisos indicated at the end of this letter. All changes must be made before data collection commences. The Committee does not need to see evidence of these changes, however supervisors are responsible for ensuring that students implement any requested changes before data collection commences.

Important COVID-19 update: Please consult the latest College guidance (linked below) and ensure you have completed the risk assessment procedure prior to any data collection involving face-to-face participant interactions.

https://internal.kcl.ac.uk/innovation/research/ethics/applications/COVID-19-Update-for-Researchers

Please ensure that you follow all relevant guidance as laid out in the King's College London Guidelines on Good Practice in Academic Research (http://www.kcl.ac.uk/college/policyzone/index.php?id=247).

For your information, ethical approval has been granted for 3 years from 18 February 2022. If you need approval beyond this point, you will need to apply for an extension at least two weeks before this. You will be required to explain the reasons for the extension. However, you will not need to submit a full re-application unless the protocol has changed. You will not be sent a reminder when it is due to lapse.

Ethical approval is required to cover the data-collection phase of the study. This will be until the date specified in this letter. However, you do not need ethical approval to cover subsequent data analysis or publication of the results.

Please ensure that you follow the guidelines for good research practice as laid out in UKRIO's Code of Practice for research: http://ukrio.org/publications/code-of-practice-for-research/.

If you do not start the project within three months of this letter please contact the Research Ethics Office.

Please note that you will be required to obtain approval to modify the study. This also encompasses extensions to periods of approval. Please refer to the URL below for further guidance about the process:

https://internal.kcl.ac.uk/innovation/research/ethics/applications/modifications.aspx

Data Protection Registration

As you have indicated in Section E that personal data will be processed as part of this research project, this letter also confirms that you have also met your requirements for registering this processing activity with King's College London. This is required in line with the College's role as a Data Controller, in accordance with the UK General Data Protection Regulation (UK GDPR).

Please note it is the responsibility of the researcher(s) to ensure compliance with other aspects of the UK GDPR, more information about this can be found here: https://internal.kcl.ac.uk/innovation/research/Research-Governance/how-does-uk-data-protection-law-affect-research/how-does-uk-dp-law-affect-research

You are required to adhere to all research data/records management and storage procedures agreed to as part of your application. This will be expected even after the completion of the study.

If there are any changes to the project that will impact on how you will you collect, manage or otherwise use your data, these must also be reflected in a modification request as outlined above.

Please would you also note that we may, for the purposes of audit, contact you from time to time to ascertain the status of your research.

If you have any query about any aspect of this ethical approval, please contact your panel/committee administrator in the first instance (https://internal.kcl.ac.uk/innovation/research/ethics/contact.aspx)

We wish you every success with this work.

Yours sincerely,

Participation in conferences

1. An oral presentation titled "A systematic review of outcome measures for balance in stroke rehabilitation" in the 7th Neurological Disorders and stroke on the 21st - 22nd of February 2022, (https://www.ctsnet.org/events/7th-international-conference-neurological-disorders-and-stroke).

2. An oral presentation titled "Dual tasking assessment and rehabilitation in stroke survivors" in the Neurology conference (https://www.pulsusconference.com/) on 29th of June 2023.

3. An e-poster presentation titled "Factors associated with balance and functional gait in ambulatory stroke survivors" in the World Stroke Congress, which was between 10th - 12th of October 2023, (https://worldstrokecongress.org/)

4. A poster presentation titled "Feasibility of HOLOBalance for balance training for ambulatory stroke survivors" in the UK stroke forum which held on 4th - 6th of December 2023, (https://www.stroke.org.uk/professionals/uk-stroke-forum/uksf-programme)

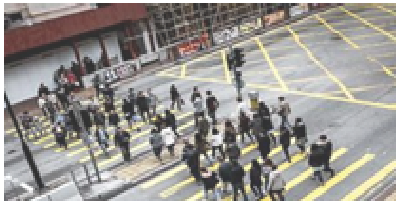
Factors associated with functional gait in stroke survivors vs healthy controls.

Kawthar Ajaj, Stephen Harridge, Isaac Sorinola, Marousa Pavlou
Centre for Human & Applied Physiological Sciences, King's College London

Background and aims

Community ambulation does not only require the ability to walk independently but also to navigate surroundings and carry out tasks while walking (i.e., functional gait).

The aim of this study was to identify factors associated with functional gait in stroke survivor's vs healthy controls.



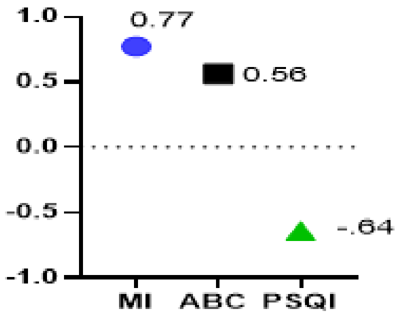
Methods

20 chronic stroke survivors able to walk independently and had a MoCA score >22; and 20 healthy controls were recruited; mean(X̄) age (±SD)= 59±9.8, 64±10.9 years, respectively.

Primary OM	Functional Gait Assessment (FGA)
Secondary OM	The Motricity Index (MI) for motor recovery
	Montreal Cognitive Assessment (MoCA)
	Subjective symptoms: The Activity Balance Confidence Scale (ABC) Hospital Anxiety and Depression Scale (HAD) Pittsburgh Sleep Quality Index (PSQI)

Findings

- Significant between-group differences were observed for FGA scores ($p<0.001$).
- In the stroke group, there was positive association between FGA and MI, and ABC scale. Also, a negative association with PSQI. (Spearman's rho presented in the graph). No association was observed with cognitive function, depression, and anxiety levels.
- In healthy controls, no association with FGA.



Conclusion

Balance confidence is a key factor in functional gait as is the quality of sleep, in chronic stroke survivors. Although these findings need to be confirmed in larger studies, balance confidence and sleep should be included within the assessment protocol for functional gait retraining.

Key resources

Wrisley et al, 2004
Nasreddine et al, 2005
Tyson et al, 2018
Shumway-cook et al, 2005

KING'S College LONDON

Feasibility of augmented reality HOLOBalance intervention programme for balance training for stroke survivors

Kawthar Ajaj, Stephen Harridge, Isaac Sorinola, Marousa Pavlou
Centre for Human & Applied Physiological Sciences, King's College London

Background

About 83% of stroke survivors consider balance dysfunction as a distressing problem and affects their daily life activities. Individualized treatment is recommended; however, compliance is challenging, and it is costly to provide. An individualised tele-rehabilitation balance physiotherapy programme using holograms to deliver the exercises (HOLOBalance) could address this challenge.

Purpose of the study

1. To investigate the feasibility and acceptability of a supervised HOLOBalance programme in stroke survivors.
2. To explore trends for effectiveness in balance and cognitive function, and subjective symptoms.

Methods

Eight chronic stroke survivors able to walk independently were recruited for an 8-week (16 sessions) HOLOBlance programme. The sessions were delivered in a laboratory setting at King's College London.
The HOLOBalance programme consists of multisensory rehabilitation exercises, cognitive and auditory training.

Assessment

- Exit interviews, the System Usability Scale (SUS)
- Balance Evaluation System Test (Mini-BESTest), Functional Gait Assessment (FGA)
- The Activity Balance Confidence (ABC), the Falls Efficacy Scale (FES), the World Health Organization Disability Assessment Schedule (WHODAS)

Virtual therapist from the HOLOBalance programme

Results

- No adverse events were recorded, only one participant dropped out due to unrelated issue.
- Exit interviews revealed the system was acceptable, one participant commented "after I joined, I was able to travel alone first time since I had the stroke".
- 3 participants rated the programme in the SUS ≥ 75% indicating excellent usability, other four participants had above 50% (i.e., good usability).
- Tendency of improvement in the secondary outcomes are shown in the following tables

increase in score % change	
Mini-BESTest	13% to 32%
FGA	13% to 27%
ABC scale	16% to 200%

decrease in score % change	
WHODAS	9% to 120%
FES	4% to 64%

Conclusion

The HOLOBalance intervention programme was feasible and acceptable for stroke survivors. Dynamic balance and functional gait and subjective symptoms showed trends of improvement. Further studies are needed to address the feasibility of HOLOBalance for stroke in home environment.

Key references

Gatsios et al, 2019
Liston et al, 2020
Liston et al, 2014
Rendon et al, 2014