Computerised Automated Feedback System for Sit-to-Stand Training

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(Siu Fai Ho)

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Acknowledgements

When I decided to pursue a doctorate degree, everyone around me was saying pretty much the same thing: “If you are an engineer, you don’t need a PhD (or an EngD in this case). You would just be wasting your time”. Well, this thesis proves them wrong. I enjoyed every moment of this project and I believe, I pursued the right career path.

First and foremost, I would like to offer my sincerest gratitude and deep appreciation to my fantastic supervisors, Dr Andy Kerr and Dr Avril Thomson, for their invaluable support, feedback and guidance. They have been guiding me since day one of this project and still while I am writing this acknowledgement. Without them, I could have done nothing. This project and the submission of this thesis would not have been possible. Without them, I would never be able to win the best paper award and nominated for the best abstract at two international conferences. Thanks for everything!

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Abstract

The ability to stand-up from sitting declines with age. Manual rehabilitation services are being challenged by the increasingly older frailer population with patients are receiving sub-optimal access to professional therapy. Technology may offer solutions. Following a review of the literature as well as clinical observations, user surveys and interviews, an initial design specification for a computerised automated feedback system for sit-to-stand training was generated.

A virtual reality system with audio-visual feedback on performance was subsequently developed. This prototype used an inertial sensor and a portable force plate to provide raw movement data. A Kalman-filter based sensor-fusion algorithm was designed to tackle signal-processing issues. A sit-to-stand detection algorithm, using a finite state machine, then analysed and detected crucial movement events, before a fuzzy-logic decision-making algorithm generated the final audio-visual feedback presented to users in a user-friendly manner to augment their sit-to-stand training.

A phase two pilot randomised controlled trial was conducted at a geriatric rehabilitation unit. All participants underwent functional assessments and had their daily sit-to-stand and step counts recorded forty-eight hours before the study began and at the end of the trial. The experimental group received the technology augmented sit-to-stand training for four weeks, three sessions a week, while the control group received standard physiotherapy. Sixteen participants completed the trial, eight in each group. An increase in daily sit-to-stand movements and improved scores on clinical measures of mobility were all statistically significantly ($p<0.05$) better than the control group. Participants and therapists found the system motivating, intuitive and enjoyable. The computerised biofeedback was considered by users to be superior to standard therapy for providing motivation and engagement with rehabilitation. A novel, technology-based, feedback system, designed collaboratively with end-users to enhance sit-to-stand training in older adults, was found to be acceptable and feasible for clinical environments, suggesting great potential for future geriatric rehabilitation.

Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

ADL	Activities of Daily Living
AFGS	Automated Feedback Generation System
ANOVA	Analysis of Variance
CD	Compact Disc
CoM	Centre of Mass
CoP	Centre of Pressure
CPU	Central Processing Unit
DoL	Degree of Likelihood
EEG	Electroencephalogram
EMG	Electromyography
EMS	Elderly Mobility Scale
F.I.R.S.T.	Feedback Integrated Rehabilitation for Sit-to-stand Training
FIS	Fuzzy Inference System
FSM	Finite State Machine
FTSTS	Five Times Sit to Stand
GPS	Global Positioning System
GRF	Ground Reaction Force
HD	High Definition
IMU	Inertial Measurement Unit
kP	Kilopixel
KP	Knowledge of Performance

KR	Knowledge of Results
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
MATLAB	Matrix Laboratory
MEMS	Microelectromechanical Systems
MoCA	Montreal Cognitive Assessment
MP	Megapixel
MRC	Medical Research Council
NASA	National Aeronautics and Space Administration
NHS	National Health Service
PDS	Product Design Specification
RAM	Random Access Memory
RCT	Randomised Controlled Trial
RGB	Red Green Blue
SCAMPER	Substitute, Combine, Adapt, Modify, Put to another use, Eliminate and Reverse
SD	Standard Deviation
SMC	Sequential Monte Carlo
STS	Sit-to-Stand
TAT	Tinetti Assessment Tool
UCD	User Centred Design
USB	Universal Serial Bus
VFS	Visual Feedback System
VR	Virtual Reality
WIMP	Windows, Icon, Mouse and Pull-down menu

Awards and Nominations Related to Thesis

Best Paper Award:

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Research Output Related to Thesis

1. Ho, S. F., Thomson, A., Kerr, A. (2015). Computerised rehabilitation system for sit-to-stand training in stroke survivors: engaging the users in the design process. The Society of Research in Rehabilitation Summer 2015 Conference, Newcastle upon Tyne, U.K., 9th June 2015. Poster Presentation.

2. Ho, S. F., Thomson, A., Kerr, A. (2015). The development of a diagnostic platform for the functional evaluation of the sit-to-stand movement in stroke survivors. The 9th IEEE EMBS UKRI Postgraduate Conference on Biomedical Engineering and Medical Physics 2015, Liverpool, U.K., 14th-16th July 2015. Oral Presentation.

3. Ho, S. F., Thomson, A., Kerr, A. (2016). The development and evaluation of a sensor-fusion and adaptive algorithm for detecting real-time upper trunk kinematics, phases and timing of the sit-to-stand movements in stroke survivors. ICSAE Conference 2016, Liverpool, U.K., 20th-21st October 2016. Oral Presentation.

4. Ho, S. F., Thomson, A., & Kerr, A. (2017). The development and evaluation of a sensor-fusion and adaptive algorithm for detecting real-time upper-trunk kinematics, phases and timing of the sit-to-stand movements in stroke survivors. In 2016 ICSAE Conference, ICSAE 2016 (pp. 447–451). Newcastle upon Tyne, England, United Kingdom: IEEE Xplore. https://doi.org/10.1109/ICSAE.2016.7810233, Peer-Reviewed and Published Conference Paper.

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6. Ho, S. F., Thomson, A., & Kerr, A. (2017). Technology for training the sit-to-stand movement in stroke survivors: a systematic literature review. The 14th Congress of the European Forum for Research in Rehabilitation 2017, Glasgow, U.K., 24th-27th May 2017. Poster Presentation.

7. Ho, S. F., Thomson, A., & Kerr, A. (2017). The validation of a therapeutic feedback generation system for evaluating the sit-to-stand performance in stroke survivors. British Society of Rehabilitation Medicine Annual Conference 2017, London, U.K. 18th-19th July 2017. Poster Presentation.

8. Ho, S. F., Thomson, A., & Kerr, A. (2017). Development of the FIRST system: feedback Integrated Rehabilitation for Sit-to-stand Training – design, feasibility and usability. International Neurorehabilitation

Symposium 2017, London, U.K., 17th-20th July 2017, Poster Presentation.

9. Ho, S. F., Thomson, A., & Kerr, A. (2018). Feedback Integrated Rehabilitation for Sit-to-stand Training (FIRST): A Pilot Randomised Controlled Trial. British Geriatric Society Spring Meeting 2018, Nottingham, U.K., 11th-13th April 2018. Poster Presentation, Short Oral Presentation and Abstract (To be published on Age and Ageing).

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Chapter 1 – Introduction

1.1 Age-Associated Frailty

Ageing is a natural physiological process that occurs throughout life. This process can ultimately lead to frailty, which is a multidimensional geriatric syndrome of increased vulnerability due to ageing-associated deterioration of physiological functions (Qian-Li, 2011). The definition of frailty in medicine first appeared in 1990 as a Medical Subject Heading in the U.S. National Library of Medicine. It defines frailty as “older adults or aged individuals who are lacking in general strength and are unusually susceptible to disease or to other infirmities” (U.S. National Library of Medicine, 1990). Frail individuals are more likely to lack the physical capacity to cope with activities of daily living (ADL) due to muscle weakness, habitual lower levels of physical activity, slow movements and impaired balance (Millán-Calenti, Maseda, Guimaraes-Pinheiro, Lorenzo, & de Labra, 2015) (Sánchez-García et al., 2017) (Sezgin, O’Donovan, Cornally, Liew, & O’Caoimh, 2019). These numerous adverse outcomes increase the risk of falls, injuries, hospitalisation and increasing dependency (Wou & Conroy, 2013). However, the effects of frailty can be reduced, prevented or even reversed through participation in appropriate physical therapy and exercises (C. H. Chou, Hwang, & Wu, 2012) (Millán-Calenti et al., 2015) (R. B. Silva, Aldoradin-Cabeza, Eslick, Phu, & Duque, 2017).

Thanks to better healthcare and understanding in nutrition, the average human lifespan has dramatically increased during the twentieth century. Life expectancy in developed countries has risen by over 30 years in the past decades (United Nations, Department of Economic and Social Affairs, 2015). Many developing countries are also experiencing a similar demographic change (Shetty, 2012). Worldwide, the population of individuals aged 60 years or above increased from 9% in 1990 to 12% in 2013 (901 million) and is projected to reach 21% by 2050 (2.1 billion) (Sander et al., 2015). With this progressively ageing population, preventing and reducing the progression of frailty is becoming increasingly important, placing growing demands on rehabilitation services.

1.2 Age-Associated Comorbidity and Disability

As well as frailty, there is a range of diseases that occurs more frequently in older adults, causing physical disability and limiting their ability to live an independent life. One of these conditions is stroke, the most frequent cause of disability among older adults (Adamson, Beswick, & Ebrahim, 2004). It is estimated that 74% of stroke incidents in the U.K. are recorded from people 65 years old or above, in contrast to only 0.6% of cases that occur in the under 20 years old population (Johnson, 2003). This neurological condition is triggered by an interruption of the supply of blood to the brain due to an ischaemia (obstruction within a blood vessel) or a haemorrhage (burst of a blood vessel) which restricts the provision of oxygen and essential nutrition to the affected area of the brain. This sudden damage causes brain cells in the region to die, creating a “neurological lesion” as the brain rapidly loses its functions (Markus, 2012). The anterior circulatory system is particularly vulnerable to this injury and affecting parts of the brain that control body trunk and limbs movements. Consequently, 65% of stroke patients suffer from hemiparesis (reduced muscle strength on one side of the body) or hemiplegia (lack of control on one side of the body) (Jongbloed, 1986) and are left with physical deficiencies that restrict their physical functions (Mollaoĝlu, Fertelli, & Tuncay, 2011).

Another condition that also limits mobility is Parkinson’s disease, one of the most common age-related neurodegenerative diseases with 95% of all patients are above the age of 60. The Parkinson’s disease process primarily affects the basal ganglia, reducing production of dopamine which impairs the brain’s ability to regulate the motor system (Reeve, Simcox, & Turnbull, 2014) (K. Park, Roemmich, Elrod, Hass, & Hsiao-Wecksler, 2016). Cardinal symptoms, such as postural abnormalities, bradykinesia, akinesia and tremors, challenge Parkinson’s patients in controlling their body movements and the safe execution of simple ADLs, like sit-to-stand (STS) and gait, which are critical to daily activities (Salarian, Russmann, Vingerhoets, Burkhard, & Aminian, 2007).

Osteoarthritis, a degenerative joint disease, results from the breakdown of joint cartilage due to chondrocyte changes and is closely associated with ageing.

55% of individuals diagnosed with the condition are 65 years old and above, while only 7.6% in the population aged 45 and younger (Y. Li, Wei, Zhou, & Wei, 2013). This condition causes symptoms of pain and restricted movements, particularly in the spine and weight-bearing joints, such as the hip or knee. This increases the difficulty of day-to-day tasks and leads to further impairment through disuse atrophy as individuals seek symptom relief by unloading the affected joints (Valderrabano & Steiger, 2011).

1.3 Importance of The Sit-to-Stand Movement

The physical impairments associated with these conditions can restrict, or even prevent, the execution of the sit-to-stand (STS) transfer, a movement that describes the body posture when a person is rising from a sitting position to standing upright (K. M. Kerr, White, Barr, & Mollan, 1997). This key functional movement is recognised as a prerequisite for gait motion (Kralj, Jaeger, & Munih, 1990). Before someone is able to walk, they must be able to stand. The movement is identified as being critical to ADLs and executed, on average, sixty times each day by healthy individuals in the course of their everyday activities (Dall & Kerr, 2010). From leaving the bedside in the morning, to use of the bathroom and travelling on public transport, individuals need the capacity to safely perform the STS movement independently. Failure to perform this movement safely and independently increases the frequency of falls, dependency and burdens on healthcare providers (Cheng et al., 1998). Therefore, regaining safe and independent STS ability is a stated primary goal in rehabilitation (Barreca, Sigouin, Lambert, & Ansley, 2004). Understanding how best to restore independence in this movement is, therefore, considered a priority for rehabilitation research across many conditions associated with ageing.

1.4 The Need for Rehabilitation Technology

Typically, patients train the STS movement with professional rehabilitation staff who provide manual support, motivation and feedback on performance. The Bobath concept, also called neuro-developmental treatment, is the most widely adopted rehabilitation approach used in the treatment of neurological conditions (Kollen et al., 2009). The main intervention strategy for this concept lies with the physiotherapist providing manual hands-on support to patients in order to facilitate movements through the use of sensory information (i.e. verbal instructions and tactile cues delivered by physical contacts) while inhibiting patients adopting abnormal postures, which could interfere with optimal performance.

This professionally supervised rehabilitation is heavily reliant on rehabilitation staff, placing a bottleneck on rehabilitation service delivery and, potentially, restricting outcomes. Recent U.K. government health budgets have seen over 90% of rehabilitation providers in England, U.K. are experiencing or expected to see, a reduction in services (Chartered Society of Physiotherapy, 2012).

All these issues present a challenge to rehabilitation providers aiming to meet national, evidence-based, guidelines. For example, stroke survivors are recommended to receive “at least forty-five minutes of each appropriate therapy every day, at a frequency that enables them to meet their rehabilitation goals” (Intercollegiate Stroke Working Party, 2008). However, studies suggest that this recommendation is not being achieved for most patients in the U.K. (Royal College of Physicians, 2015) (Clarke et al., 2015) (Luker, Lynch, Bernhardsson, Bennett, & Bernhardt, 2015). Stroke survivors, for example, are now receiving less than optimal rehabilitation experience, potentially limiting recovery outcomes.

Technology may offer solutions to increase the opportunity for safe and repetitive practice of functional movements, like the STS movement, without an increased burden on funded services. Such rehabilitation technologies can also promote self-management at homes by allowing patients to practice without the presence of therapists or assisted training in the clinical environment while minimising therapist time consumption (Timmermans, Seelen, Willmann, & Kingma, 2009). Consequently, the use of technology in rehabilitation has shown to increase the time and frequency of practice (Meijer, Graafland, Goslings, & Schijven, 2018) (Jack et al., 2001). Perhaps, more importantly, they appear to have positive psychological effects on the patient’s motivation and engagement in rehabilitation (Cardoso et al., 2006). In terms of socioeconomically effectiveness, technology has been demonstrated to reduce long-term rehabilitation and care costs that are borne by the domiciliary and institutional care providers and non-medical societal expenses, including benefit payments and lack of social participation (Labella et al., 2009).

1.5 The Needs of End-User Inputs

The rising demand for cost-effective therapy has driven a higher usage of technology in addition to standard manual training (A.-M. Hughes et al., 2014). This generates a rapid increase in research and development on the use of technology as a complementary tool to provide augmented exercises in rehabilitation (Skjæret et al., 2016). While there has been some empirical research to support the use of rehabilitation technologies, adoption among users (therapists and patients) is slow with only a small percentage of technologies being implemented into routine clinical practice (A.-M. Hughes et al., 2014). A likely reason for the poor engagement with technology is the lack of user involvement in the traditional design process which excludes stakeholders from the technology-driven development and only involves them at the evaluation stage. Involving technology in the direct delivery of rehabilitation can be counter-intuitive to therapists who are educated in a traditional, hands-on approach, to rehabilitation. There is, therefore, a risk of failure due to non-adoption.

Engaging users throughout the design process is key to technology adoption (Ghazali, Ariffin, & Omar, 2014) and potentially reduces the risk of non-adoption. Therefore, a user centred design (UCD) process has been adopted in this thesis to maximise the potential for translation to everyday practice.

The Total Design Framework provides a structured UCD process as shown in figure 1 (Pugh, 1991). This framework starts from investigating the market needs before any design work, outlining the product specifications, generating initial concepts using illustrations or models, producing prototypes for testing, manufacturing and procurement plans to constantly reviewing the market after release.

In this thesis, a modified version of the framework was adopted. This is to overcome challenges faced when adopting technology into a clinical environment, such as the National Health Service (NHS), since it is considered an important step for adoption of rehabilitation technologies (Andrew Kerr, Smith, Reid, & Baillie, 2018). This iterative design process involves multiple interactions with users to generate the initial device attributes and design specifications which are subject to an evaluation process. Users' needs and requirements were first investigated, then engineering concepts for the new system were generated using concept development tools. User opinions and feedback were then sought during subsequent evaluation and clinical trials. Less emphasis was placed on the commercial and manufacturing aspects. Therefore, a modified total design framework was adopted as explained further in section 3.2.

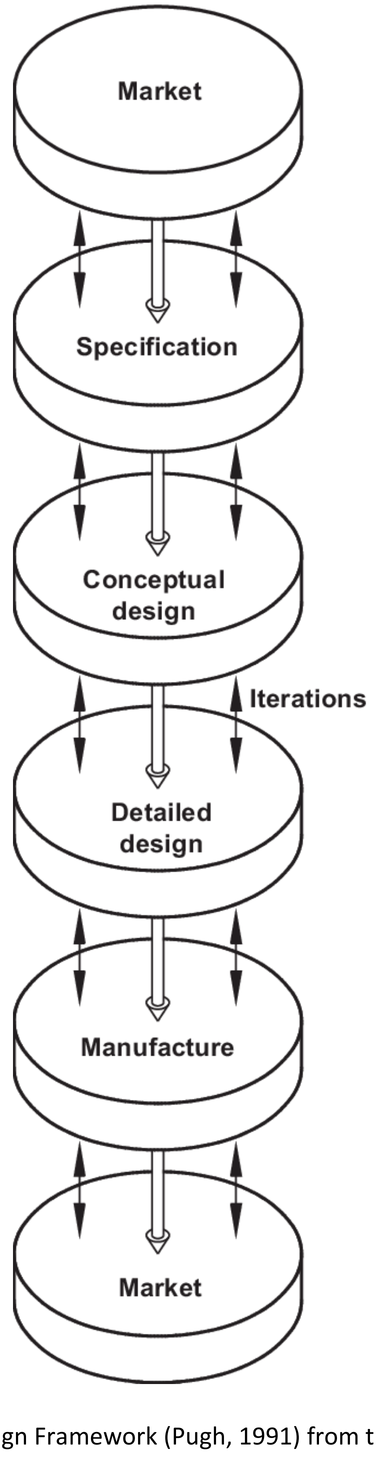


Figure 1: The Total Design Framework (Pugh, 1991) from the marketing stage to the manufacturing stage.

1.6 Feasibility - Randomised Controlled Trial

In healthcare, complex interventions consisted of numerous interrelating elements which appear to be vital for an intervention to function properly, such as frequency and timing of therapy, setting and location where therapy is being provided, type of clinicians and their behaviour. It could be difficult to pinpoint the exact factors that made an intervention to be effective. Separating and understanding each of these interactions of complicated factors are even more problematic.

The UK's Medical Research Council (MRC) has provided a framework guiding the development and evaluation of RCTs for complex interventions in healthcare settings (Moulding, Silagy, & Weller, 1999). Later, Craig et al., (2008) published a revised framework and guidance for development and evaluation of complex interventions. This revised framework has been widely adopted across disciplines (Bobrow et al., 2018) and successfully implemented in user-centred design processes for developing technology-based systems for healthcare (Moore et al., 2018).

The framework is distinguished by four stages. The theoretical phase (pre-clinical phase) is the first stage in evaluating a complex intervention. In this step, informal evidence, such as opinions from therapists, is gathered and theoretical theory is formed to suggest the hypothesis is feasible before designing the study.

The second stage (phase 1) is the modelling phase in which different elements in a complex intervention are identified, their interrelationships and influence on the interventions are also examined using qualitative analysis, such as focus-group interviews with users, stakeholder surveys and observational studies.

During the third stage (phase 2), a pilot RCT is conducted to test the feasibility of the trialling study. This is to examine various components and their treatment effects in an intervention. In a pilot RCT, participants are randomly assigned to one or more intervention groups, such as an experimental group which receives the trialling intervention and a control group which receives the usual treatments.

The fourth stage is the long-term surveillance phase in which a separate study, likely to involve observations, is conducted to establish the real-life and long-term effectiveness of the intervention.

Randomised controlled trial (RCT) is considered as the “gold standard” study design for assessing the effectiveness of complex interventions (Cook, Levinson, & Garside, 2011) and the most statistically rigorous method for testing hypothesis comprehensively while examining interrelating factors (Moulding et al., 1999). The random assignment means participants with different attributes that may affect the final outcomes, for example, age, reasons for admission, level of disability, comorbidities etc, could be selected to any groups. This prevents intentional allocation of participants to influence the study results and reduces the potential for bias. This is the main advantage of RCTs as it is easier to indicate causation and effects. More balanced systematic differences between trial groups are expected compared to other methods of evaluation research, like observational, cohort and case studies, which are non-randomised (Barton, 2000).

Participants in both trial groups will be observed and outcomes are assessed in the same way before and at the end of the trial. The data gathered can then be compared and any differences in clinical outcomes could due to the treatment being tested. The results provide information about acceptability and feasibility. They can also be used to identify appropriate outcome measures and estimates of recruitment for the main trial (Phase 3). Therefore, a phase 2 pilot RCT design was chosen as the design for this thesis.

1.7 Aim of Thesis

The aim of this thesis, therefore, was to design and test a rehabilitation technology that optimises training of the STS movement in a geriatric rehabilitation population and promote self-management. The design of such a device will be informed by the patients’ and healthcare professionals’ perceptions and experiences of recovering this important movement through rehabilitation and which could be feasibly delivered within the current clinical model.

This device targets older adults with impaired mobility, in particular, an impaired ability to stand up from a chair. This will include individuals with a range of mobility impairing conditions, such as stroke, Parkinson’s disease and degenerative joint diseases, like osteoarthritis, as well as people simply identified as being frail. Patients with specific cognitive disorders will not be considered in this study.

1.8 Organisation of Thesis

Chapter 2 will present an overview of the existing literature. The findings from this literature review will provide an analysis of the suitability of current systems for use in rehabilitation and suggestions for new systems and research designs that can be reasonably implemented with the current clinical model in geriatric rehabilitation. This will be informed by an initial review of the STS movement in geriatric population and the importance of feedback during rehabilitation.

Chapter 3 will consider users’ preferences and opinions of a potential STS training system using a user centred design process that is based on the total design framework. This will involve a series of clinical observational sessions, distribution of designed questionnaires and semi-structured interviews with the stakeholders. The findings will contribute to the generation of a product design specification, a document that outlines all the design factors and user requirements that must be fulfilled to maximise the adoptability of such an STS training system and lay the groundwork at the beginning of all the subsequent engineering design activities.

Chapter 4 will describe and justify the development of a Kalman-filter based sensor-fusion algorithm with error compensation to process and integrate the real-time raw signals obtained from an inertial sensor and a portable force plate. The development of a finite stated machine based STS detection algorithm, which analyses and detects crucial events of the movement, including the transition of phases and timing of the movement, will then be described. Both algorithms were dedicated for use in mobility-impaired older adults.

Chapter 5 will provide an overview of the development of an automated feedback platform for the STS movement. This is based on a fuzzy inference system for performance evaluation and detection of anomalies, such as force-symmetry loading, an inadequate impulse for push during rising and postural instability. The development of a virtual-reality based visual feedback system will also be presented and discussed in this chapter.

Chapter 6 will describe and discuss a pilot randomised controlled trial which was conducted at a geriatric rehabilitation unit, primarily to test the acceptability and feasibility of the system in a clinical environment as well as gather pilot data on effectiveness.

The concluding chapter, chapter 7, will discuss the whole contribution of this project and present recommendations for further work.

Chapter 2 – Rehabilitation Technology for Re-training Functional Movements with a Focus on the Sit-to-Stand Movement: An Overview

2.1 Introduction

This chapter will outline the biomechanical difficulties that potentially restrict performance of the sit-to-stand (STS) movement, with a particular focus on older adults. The importance of feedback in motor relearning and rehabilitation will also be presented as it related to the recovery of functional movements, such as the STS movement. Finally, the chapter will consider the research activity in the use of rehabilitation technologies to enhance the recovery of functional movements. It will describe these technologies, identify their limitations, both in the technology and applications and critique the evidence for their efficacy. This study focuses on technologies that provide feedback and not mechanical assistance, because feedback is considered a key role in motor relearning. It was considered to be a priority by therapy staff as it allows more self-rehabilitation in routine clinical setting and at homes.

2.2 Ageing and the Sit-to-Stand Movements

The STS movement is particularly challenging for geriatric population (Hortobagyi, Mizelle, Beam, & DeVita, 2003), many of whom may be able to walk unaided without extra support but struggle to execute this movement independently (Aissaoui & Dansereau, 2003) (Mombaur & Ho Hoang, 2017). This is because the physiological process of ageing reduces muscle power specifically (Skelton, Kennedy, & Rutherford, 2002). Potentially, this leaves older people with insufficient capability for generating the vertical momentum required for standing up successfully (Tsuji, Tsunoda, Mitsuishi, & Okura, 2015). A decline in neural function (reduced nerve conduction velocity) can lead to balance impairments, decrease in dynamic stability and poor steadiness when executing the STS movement (Tung, Yang, Lee, & Wang, 2010). Psychological factors, such as depression and the presence of pain, may also have a negative impact on STS performance in older people (Lord & Menz, 2002).

2.3 Biomechanics of the Sit-to-Stand Movement

As shown in figure 2, the STS movement can be distinguished into four transitional phases of transferring the body of support from “seat” to “feet” (Schenkman, Berger, Riley, Mann, & Hodge, 1990) (Boukadida, Piotte, Dehail, & Nadeau, 2015a).

Phase 1: The flexion-momentum phase begins with an initiation of the movement. The pelvis tilts anteriorly and the trunk leans forward, primarily through hip flexion. This movement generates the necessary forward horizontal momentum required for standing up and moving to a new base of support.

Phase 2: The momentum-transfer phase begins with the lifting off from the seat. The upper-trunk continues to move forward while ankle joint dorsiflexion occurs at both ankles. During this phase, the horizontal momentum developed in phase 1 transfers to the whole body through hamstring and gluteal activity for upward movement as well as continuing forward movement. As soon as the body reached its maximal anterior point and maximal ankle dorsiflexion, the hips and trunk begin to extend to lift the body and this signals the start of phase 3.

Phase 3: This phase is all about vertical momentum. The extension phase commences after peak ankle dorsiflexion and ends when the hips cease to extend, and the body is no longer moving forwards.

Phase 4: The final, stabilisation phase begins when the hip-extension velocity reaches zero and continues until all movements (e.g. movements of arms, feet and ankles) stop or are within a normal range of motion. The STS movement completes at this phase when the person has achieved a stable upright standing posture.

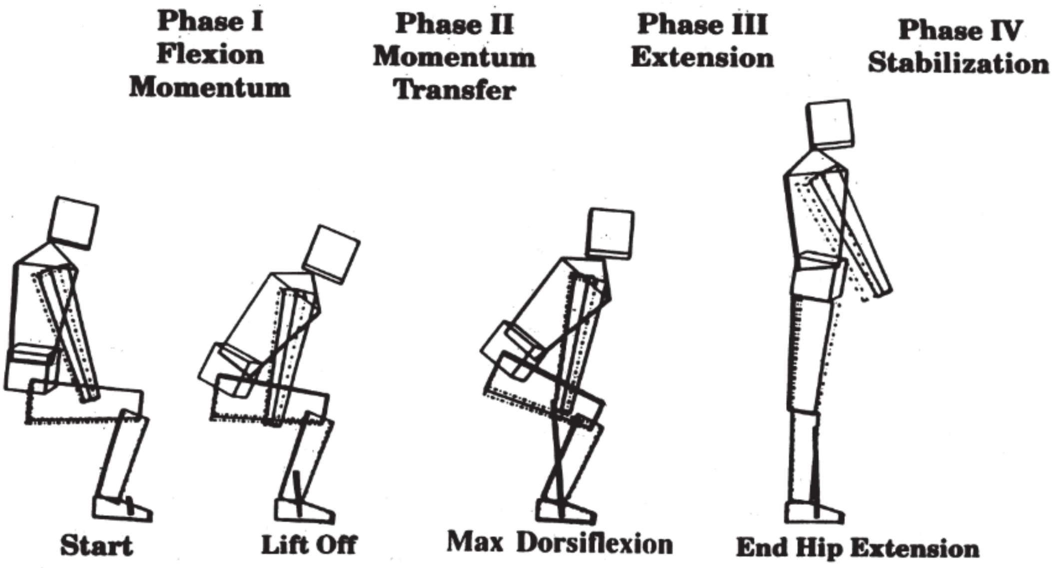


Figure 2: This figure illustrates drawings of human models standing up during the four phases of the STS movement from the sagittal plane of view (Schenkman et al., 1990).

2.4 Biomechanics of Sit-to-Stand in Older People

Due to the well reported difficulties older people have when performing this movement, researchers have conducted biomechanical studies to characterise STS performance and identify the specific impairments in older people performing this movement. The STS movement is recognised as one of the most demanding activities of daily living (ADL), especially in geriatric population (Hughes & Schenkman, 1996) as the successfulness of this movement requires dynamic force-symmetry control (Fujimoto & Chou, 2012), adequate muscle strength to create an impulse for push when rising (Lomaglio & Eng, 2005) and appropriate postural co-ordination (Janssen, Bussman, Horemans, & Stam, 2005).

In fact, these three factors mentioned above are associated with the stability of the movement (Lord, Murray, Chapman, Munro, & Tiedemann, 2002). They are considered as the key features for failing to stand-up and often used to compare the STS performance in older adults with other groups of individuals, such as younger population (Schwenk, Gogulla, Englert, Czempik, & Hauer, 2012) (Adame et al., 2012) (Regterschot et al., 2013) (Cadore & Izquierdo, 2013) (Fontecha, Navarro, Hervás, & Bravo, 2013) (Boukadida et al., 2015a) (Dolecka, Ownsworth, & Kuys, 2015).

Physical performance of the movement can simply be visually assessed by therapists (AGILE, 2012). However, the involvement of human errors is likely when healthcare professionals analyses physical activities (Scheirton, Mu, & Lohman, 2003). It has been reported that the accuracy and sensitivity of assessments made by physiotherapists with different levels of experience could vary significantly, potentially affecting clinical outcomes (Dickens, Fazal, Gent, & Rees, 2003). Technologies, such as optoelectronics 3D motion capture systems (Fritz et al., 2011), force plates (Beckham, Suchomel, & Mizuguchi, 2014) and body worn motion sensors (Papi, Osei-Kuffour, Chen, & McGregor, 2015) provide information on movements with more robust measurement properties. These have been adopted into research aimed at analysing a wide range of human movements, including the STS movement. The following sections describe the difficulties older people experience when standing up as informed by research using these biomechanical measurement instruments.

2.4.1 Stability

When sitting, the body is supported by a chair and the ground and is, therefore, very stable. But when transferring to a standing up position, the chair no longer provides support and the body will become less stable. During the transfer phase, as the body lifts off the chair, the body's centre of mass (CoM) will be furthest away from the new base of support, which is defined as the area enclosed by the feet (Mazzà, Zok, & Della Croce, 2005). At this point, if the body is unable to maintain force-symmetry control and keep the body upright (e.g. weakness on one leg or the upper-trunk moved further away laterally than it should), a small deviation will result in a moment induced by the gravity with the body accelerating back down towards the chair or the ground (Maurer & Peterka, 2005) with the possible risk of injury. If the lower trunk cannot generate a force to counteract this transient loss of symmetry, a fall would occur.

A study involving 503 participants examined the force-symmetry variations between younger individuals and older people during STS transfers (Yamako, Chosa, Totoribe, Fukao, & Deng, 2017). No participants had any known illnesses related to the musculoskeletal system which could limit their STS performance. They were assigned into seven "10-year" age groups. A force plate was used to measure the centre of pressure (CoP) in the transverse plane when standing up. This measurement system provided an estimate of the body's CoP during motions and was considered to be a good representation of force-symmetry (Benda, Riley, & Krebs, 1994). The study calculated a “balance score” based on that measurement. It found that the sway in CoP when standing up was largest in the oldest age group, aged 80 to 89 (“balance score”: 3.4 ± 0.7) compared to the younger group, such as aged 20-29 with a “balance score” of 4.5 ± 1.0 (Yamako et al., 2017).

Research carried out by Chou et al. (2003) with forty older hemiplegia patients and twenty-two age-matched healthy participants showed on average, the hemiplegia patients had 61% higher variation in lateral CoP movement than the healthy individuals as recorded by a force plate and a motion capture system. This result revealed force-symmetry control in older people, especially individuals with physical impairments, was limited compared to younger individuals when standing up (S. W. Chou et al., 2003).

Seven hundred frequent fallers and non-fallers were invited to take part in a study regarding force-symmetry control when standing up (Zhou, Habtemariam, Iloputaife, Lipsitz, & Manor, 2017). The results showed participants with a higher fall rate had larger postural sway and poorer stability when standing, as defined by the variation in lateral CoP, than the non-fallers by a force plate. This is because the fallers struggled to maintain symmetry. However, other kinematic parameters, such as the rate of change of sway and area of sway, between the groups were the same and independent to force-symmetry control. Other studies have also shown poor force-symmetry control that could contribute to failed STS executions and falls (Riley, Krebs, & Popat, 1997) (Lord et al., 2002) (Mat, Tan, Kamaruzzaman, & Ng, 2015).

2.4.2 Momentum-Related Failure

Momentum-related STS failures are common in frail elders (Riley et al., 1997). Lower extremity strength due to weakened muscles is considered a contributing factor to this. This is because as stated in Newton's second law of motion, rising vertically from a chair will require an unbalanced force, a force generated by the lower limbs, which must exceed the full body weight.

Hughes and colleagues (1996) conducted a study on finding the knee strength that required by older people and younger individuals in order to achieve their lowest successful STS transfer (Hughes, Myers, & Schenkman, 1996). Using a force plate and a motion capture system, they found the older participants required 97 ± 22.8% of all available knee strength in order to rise successfully while the younger participants only required 39 ± 8.1%, that is a 58% difference in their available knee strength. The measured maximum isometric leg strength generated by the older participants was 103 ± 22.7Nm and the younger participants measurements were significantly greater, more than doubled, at 276 ± 62.6Nm.

The large percentage need for available knee strength (i.e. over 100%) for standing up resulting in STS failures in many older people (Masakazu, Kenichi, & Reiji, 2013). This is because insufficient momentum is generated during the momentum-transfer phase and the lack of strength cannot create moments large enough to exceed the pull of gravity. Etnyre and Thomas (2007) carried out an experiment on one hundred healthy adults. The results discovered the peak ground reaction force (GRF) generated during a successful STS transition was around 119% of the full body weight. This measurement was considered as an indication of the muscle strength required for standing up (Etnyre & Thomas, 2007). Other studies (Fleming, Wilson, & Pendergast, 1991) (Lindemann et al., 2003) have also provided similar results and demonstrated lower limbs weaknesses can be measured with a force plate by interpreting the maximum GRF applied when standing up.

To compensate for muscle weakness, older people may adopt other strategies, for example using upper-limbs for support. Etnyre & Thomas (2007) also found, their participants who used armrests for support exerted around 19.5% of the full body weight on the armrests as recorded by a force plate. The use of arm force in addition to their leg force greatly improved the chances of a successful STS movement (Masakazu et al., 2013). However, many geriatric patients who have mobility impairments are still unable to stand-up even with the support from upper-limbs (Pollock, Gray, Culham, Durward, & Langhorne, 2014).

Other important factors for the generation of momentum are the trunk forward rotation velocity and the actual angle of rotation. Additional momentum can be generated during the flexion-momentum phase and transferred to vertical momentum. This would necessitate increase trunk forward rotation velocity which may not be possible for older adults (Riley et al., 1997). Older people tend to have slower muscle contraction velocities due to a selective loss of fast-twitch fibres (Akasaki et al., 2014) and this is posing a problem in generating the required momentum for standing up (Hughes & Schenkman, 1996). Fotoohabadi et al. (2010) found the optimal upper-trunk forward lean angle to generate the uplift momentum to be around 30 degrees from the original sitting position (Fotoohabadi, Tully, & Galea, 2010). Even if performed slowly, the ability to lean the trunk forward to this angle greatly reduced the consequent moment at the knee (Hughes, Weiner, Schenkman, Long, & Studenski, 1994).

2.4.3 Recovery of STS Ability

Restoring STS ability by addressing the movement impairments identified in these biomechanical studies (i.e. poor force-symmetry control, a lack of impulse for push when rising and a lack of forwarding trunk movement) could help optimise rehabilitation. Given more than a third of people aged over 65 will experience a fall every year with a tenth of these falls resulting in serious injuries, such as hip fractures (Dionyssiotis, 2012), achieving stable and safe STS transfers becomes an important therapeutic target. Strength training exercises through repeatedly practising a movement (Pedersen et al., 2015)

(French et al., 2016) have been shown to successfully recover functional movements, such as the STS movement. This currently depends on access to professional therapy staff. Rehabilitation technologies could provide a solution by delivering feedback on these identified movement parameters, when therapists are unavailable.

2.5 Rehabilitation Technologies

Innovations in technology provide new opportunities for physical rehabilitation. Researchers have provided evidence demonstrating the use of technology in training functional movements can enhance motivation (Goršič, Cikajlo, & Novak, 2017), regain better motor function with higher quality and quantity of movements (T. C. Chan et al., 2012) (Kiper et al., 2018), increase availability of rehabilitation (Papi et al., 2015) and decrease pain due to immersion in virtual-realities (Parker et al., 2016). Other studies have reported the use of rehabilitation technologies in lowering the cost of care (D J Reinkensmeyer & Boninger, 2012) as well as helping to quantify the effectiveness of therapy for more optimal treatments (Gagnon & Sabus, 2015). Technology can also promote self-management outside the clinical settings (Khanuja, Joki, Bachmann, & Cuccurullo, 2018).

However, the adoption of rehabilitation technologies is still contentious due to a number of obstacles. There is still a lack of compelling evidence showing on the use of technology compared to standard therapy, especially in the use of mechanical devices (Rose, Nam, & Chen, 2018), is superior. Moreover, the high initial cost of some devices (Qian & Bi, 2015), the needs for additional space (Yakub, Ahmad, & Mori, 2014), poorly designed human interfaces (B. Li et al., 2017), potential health and safety issues (Riva, Mantovani, & Gaggioli, 2004) and questionable efficiency (Loureiro, Harwin, Nagai, & Johnson, 2011) are considered as barriers to everyday use of these technologies.

Mechanical devices can provide mechanical assistance for user who lacks the ability to achieve the desired movements (Weber & Stein, 2018). To date, however, there has not been sufficient evidence to suggest the use of mechanical devices, such as robots, in rehabilitation is superior to hands-on manual supports (M. Zhang, Davies, & Xie, 2013). The provision of feedback, on the other hand, whether provided through technology or therapists, is a central principle in motor relearning (Stanton, Ada, Dean, & Preston, 2015).

2.6 The Importance of Movement Feedback

Movement feedback is the information received about someone’s performance of a movement task. It is crucial in motor relearning as systematic regulation of movement involves aspects of cognitive and psychomotor skills, which both could be modulated by feedback (Cech & Martin, 2012). Effective motor relearning, such as regaining STS performance in physical rehabilitation, is not only about repeating and experiencing the same movement, but also involved capturing new strategies from feedback (Fischman, 2007). This comprises active relearning to monitor and correct movement errors as well as helping to motivate individuals by tracking progress. In motor relearning, there are two major types of feedback: intrinsic feedback and extrinsic feedback.

2.6.1 Feedback

2.6.1.1 Intrinsic Feedback

Intrinsic feedback is the sensory information provided by the body's own sensory system while performing a movement. There are three main systems involved (Martini & Nath, 2009):

1) Proprioception which provides body position sense (joint position, muscle length and contact pressure) through mechanoreceptors (e.g. Ruffini endings, muscle spindles and pressure sensors embedded in the skin),
2) The vestibular system which provides information on head orientation and acceleration,
3) Vision which provides a representation of the physical environment as the movement occurs.

This intrinsic feedback is important to stabilise and refine the motor system's output as it is a closed-loop control system, providing onboard error detection and correction (Schmidt, 2011). For example, when a healthy individual is standing up from a sitting position but suddenly they sense a loss of force-symmetry to their left, the human feedback system will detect this "error" through the vestibular and visual systems primarily and attempt a “correction” to maintain stability by loading the left leg.

In fact, intrinsic feedback is an essential aspect of motor learning as it develops the cognitive processes, such as acquisition and memorisation, that allow an individual to perform a movement effectively on their own, without relying on external assistance (Lee, Swinnen, & Serrien, 1994), such as feedback from a therapist.

In 2005, Edmonds found swimmers who taught themselves to swim through various self-reflection techniques, such as correcting their own technical mistakes by sensing their movements and by imagining various conditions, improved their performance (i.e. body position in water, head position and breathing, arm stroke and leg stroke performance) more than swimmers who learnt through feedback from coaches (Edmonds, 2005).

In order to exploit the usefulness of this intrinsic feedback, an individual must understand how to formulate an internal representation of the movements. This was the subject of a study on stroke survivors by Weiss et al., 1994. Participants underwent a series of simple movements with their stronger arm: picking up a cup, holding it and then putting it down, while memorising the movements from their senses, intrinsic feedback. The participants than practised the movements mentally without any additional feedback. After that, they conducted the movements with the paralysed arm. Electroencephalogram data showed significant changes, which were considered to be due to the activation of a specific sensorimotor component in the brain, related to the internal feedback mechanisms within the human motor system, which is essential to effective motor relearning (Weiss et al., 1994).

2.6.1.2 Extrinsic Feedback

Extrinsic feedback is information from external sources, such as verbal communication from a third person, visual images played from recordings or tactile feedback provided externally. The benefit of this feedback is that it can be provided from a different perspective, for example a training coach could provide professional advice or technologies which could be used to analyse movements and provide automated feedback. It can also be used for people who may have impaired sensation, for example stroke survivors and geriatric patients, to improve the efficacy of intrinsic feedback (van Vliet & Wulf, 2006).

In another experiment providing feedback to swimmers, thirty participants were asked to control their swim pace at a certain level. They repeated the experiment three times. For the first time, no feedback was provided. Subsequently, extrinsic feedback was provided either by a coach (i.e. delivered orally and through body-language) or by an electronic device (exact timing and speed) as the participants swam. The results demonstrated that swimmers who received extrinsic feedback swam much more accurately (kept to a given pace) compared to the ones who didn't. This was believed to be because the externally provided feedback had enhanced their performance by positivity influencing the swimmer's ability to maintain their speed (Pérez, Llana, Brizuela, & Encarnación, 2009).

A study conducted on thirty-seven football players had half the participants receiving augmented feedback on jumping and sprinting performance. The feedback was provided visually as video clips and verbal instructions were provided to correct flaws. After eight training sessions, the players who received the extrinsic feedback were found to have significantly ($P < 0.05$) greater coordination in their jumping techniques and reduced kinematic factors associated with injuries (Myer et al., 2013).

Providing extrinsic feedback may be especially important for individuals with impaired cognition and perception when relearning movements (Van Dijk, Jannink, & Hermens, 2005). Delivering extrinsic feedback to people with Parkinson's disease when rehabilitating force-symmetry loading and gait was showed to improve their confidence and performance in force-symmetry loading (Shen & Mak, 2014). Similarly, amputees with consequent absence of proprioception from their missing limb, who were provided with extrinsic feedback on their actual body position and forces, were demonstrated to have better performance when using their prosthetic hand (Van Doren, Riso, & Milchus, 1991).

While extrinsic feedback is considered a vital part of motor relearning, the optimal method and timing of this feedback have not been completely resolved (Hartveld & Hegarty, 1996). The next two sections will discuss two different ways of delivering extrinsic feedback, i.e. knowledge of results and knowledge of movement performance, as well as the difference between providing feedback at different frequencies.

2.6.1.3 Knowledge of Results

Information regarding the success or failure of a task is known as knowledge of results, which is a critical variable in motor learning and relearning (Salmoni, Schmidt, & Walter, 1984) (Sharma, Chevidikunnan, Khan, & Gaowgzeh, 2016). This goal-related knowledge could be about the outcome of performing a movement (e.g. achieving an upright position from sitting), but in other circumstances, it could simply be the achievement of a pre-planned aim (e.g. standing up five times in a row) (Núñez Sánchez & Gálvez González, 2010).

Blackwell and Newell (1996) demonstrated that without the provision of knowledge of results, new motor skills could still be learnt. In their trial, participants were separated into two groups to practice an upper-limb timing task. They were asked to rotate their right arm by 30 degrees as marked on a frame within a fifth of a second. Each participant repeated the movement 200 times a day. One group received feedback in the form of knowledge of results on whether they had met the time requirement and the other group did not receive the feedback. The data acquired by an inertial sensor showed that the group which didn’t receive the knowledge of results feedback were still able to conduct the arm movement but with an absolute time error between 80 to 100 ms. However, the group which received knowledge of results in each trial had a significantly ($P < 0.01$) better performance and their absolute time error was below 20 ms (Blackwell & Newell, 1996).

Another trial was conducted on twelve national tennis players (Moran, Murphy, Cahill, & Marshall, 2004). They were assigned to two groups, an experimental group which received knowledge of results from their tennis coach during twelve weeks of training, and a control group which received no feedback at all. Training time was the same for both groups. The players who received the feedback had performed much better in follow-up tests. These trials demonstrate that knowledge of results plays a key role in motor relearning.

2.6.1.4 Knowledge of Performance

Knowledge of performance differs from knowledge of results in that it is concerned with the quality or pattern of a movement. It is movement-oriented, typically focusing on different biomechanical parameters such as velocity, displacement and momentum. This type of feedback is independent of results. For instance, an individual may have excellent force-symmetry and trunk coordination when attempting to stand up but still fails due to other factors such as knee extensor strength.

In a similar way to knowledge of results, motor relearning will not be completely inhibited if knowledge of performance is not provided (Janelle, Kim, & Singer, 1995). However, with the support of this type of feedback and combined with knowledge of results, motor relearning is undoubtedly be enhanced.

Shafizadeh, Abolfazli, & Platt (2012) demonstrated the importance of knowledge of performance when training body force-symmetry loading. Five multiple sclerosis patients took part in the blinded study. They practised force-symmetry control while standing on a force plate. The trial consisted of six 15 minutes sessions, two sessions per week for three weeks. In each trial, the participants, who were assigned to the “feedback group”, received knowledge of performance, which was generated numerically and graphically (i.e. line graphs) on a computer monitor. The feedback was about the GRF of each foot when they were standing. In the “baseline” group, the participants did not receive any feedback at all. The finding demonstrated patients who received knowledge of performance feedback improved their force-symmetry control significantly ($p < 0.001$) compared to the baseline group.

Cirstea and colleagues (2006) conducted a clinical trial on thirty-seven stroke survivors. Participants received either knowledge of results only or both knowledge of results and knowledge of performance when practising upper-limb reaching tasks. The finding shows that patients who received both types of feedback had superior performance in terms of movement precision, reduced movement time and better velocity variability than the other group (Cirstea, Ptito, & Levin, 2006). This confirms the importance of including both forms of feedback in the recovery of functional movements (i.e. motor relearning).

2.6.1.5 Frequency of Provision of Feedback

When extrinsic feedback is delivered too frequently, it may negatively interfere with motor relearning and skill retention. Studies have shown that the higher the frequency of delivering extrinsic feedback, the lower the retention of the learnt movement. A study was conducted to determine the effect of providing high versus low frequency knowledge of results in a group of individuals with developmental delay (Pfeifer, Kranz, & Scoggin, 2008). The participants were asked to create a bar with a hand movement on a computer screen which should match the one which was already presented on it. Successful trials were notified by a green light on the screen (knowledge of results). Participants who received this feedback, on each repetition, had poorer retention of the skill afterwards compared to individuals that received this feedback half of the time.

In another study (Zamani & Zarghami, 2015), forty-five participants were randomly assigned to several knowledge of performance feedback groups. All participants were learning ball tossing and were trained to toss a tennis ball at a stationary target as accurately as possible. They were allocated into three groups: 1) feedback every trial, 2) feedback every second trial, 3) no feedback at all. During trials, a score was provided. The results showed that participants who only received 50% of feedback had more accurate tosses than those in any other groups in follow-up measurements. This supported the fact that a high frequency of providing feedback does not necessarily increase performance when learning the motion or retained the skill after the training, in fact, it could be detrimental to learning. The findings do however confirm that individuals who received no feedback perform worst of all.

These results suggest that dependency on extrinsic feedback might develop over time with negative consequences for skill retention. The outcome of overreliance on extrinsic feedback could cause individuals to process intrinsic feedback signals less effectively, such as providing feedback at the end of training (i.e. conclusive feedback) (Schack, 2004).

2.6.1.6 Importance of Targeting Self-Efficacy with Feedback

Knowledge of results and knowledge of performance do not necessarily increase motivation in motor relearning. For instance, a clinical trial (Fulk & Deutsch, 2015) involving seventy-eight stroke survivors who received daily physical activity data from a wearable activity monitor (i.e. step counts, STS executions and speed of walk) found little impacts from this feedback on either walking performance or daily walking activity.

In another experiment (Saemi, Porter, Ghotbi-Varzaneh, Zarghami, & Maleki, 2012), twenty-four participants were asked to toss a tennis ball with their non-dominate arm toward a target. Group one received "good feedback" in which the feedback provided based on the best three attempts while group two received "bad feedback" which was based on their worst three tosses. Participants in the "good feedback" group achieved much higher accuracy scores (range 49 to 60). In contrast, the "bad feedback" group who received negative feedback only achieved scores between 33 and 47.

In a following up study after that trial, the "good feedback" group continued to outperform the "bad feedback" group (mean score of 52 compared to 34) demonstrating the positive effect of "good feedback" on skill retention. A self-efficacy assessment (Azim, Subki, & Yusof, 2018) was conducted on all participants. The results of the assessment indicated positive feedback promoted self-confidence and motivation (Saemi et al., 2012).

More recently, Abbas and North (2018) tested the effect of positive and negative feedback on golfing skill (Abbas & North, 2018). Thirty participants with minimal golfing experience participated. They were assigned to three different groups: 1) "Good feedback" group, 2) "Neutral feedback" group and

3) “Poor feedback” group. The “good feedback” group had the best performance (i.e. distance and direction from target holes), followed by the “neutral feedback” group and lastly, the “poor feedback” group. These findings confirm the widely held belief that feedback can have motivational properties (Wulf, Shea, & Lewthwaite, 2010). The potential for using technology to provide this feedback has not been fully exploited in rehabilitation (Hamilton, Lovarini, McCluskey, Folly de Campos, & Hassett, 2018) and could be considered a useful motivational tool as well as providing the feedback on knowledge of performance and success.

2.7 Feedback Technology for Training the Sit-to-Stand Movement

This section discusses an overview of the technology that is currently being used and in development for training the STS movement by providing feedback (success and performance). This chapter will specifically:

- Identify the strengths and weaknesses of current designs,
- Evaluate the evidence for their efficacy,
- Identify gaps for further investigation.

Most importantly, this overview will consider the clinical evidence for these systems and the main challenges for their adoption into the clinical and home environment, particularly for the geriatric population. Lastly, the chapter will compile a list of recommendations and a set of design criteria for a new STS training system.

2.7.1 Rehabilitation Technologies for Sit-to-Stand Training

A literature search was conducted in September 2014, March 2016 and again in June 2017. The searches were conducted on published peer-reviewed journal articles, conference proceedings, letters, technical reports and short papers in several databases, PubMed (from 1950), Thomson Reuters Web of Science (formerly ISI Web of Knowledge) (Science Citation Index Expanded, from 1899; Social Sciences Citation Index, from 1956; Art & Humanities Citation Index, from 1975), the Institute of Electrical and Electronics Engineering Xplore (from 1950). These four literature databases were chosen due to their popularity and coverage of biomedical engineering, physiotherapy and rehabilitation. The reference list from each article and patent databases were also hand searched.

Searched keywords were:

(sit-to-stand OR stand-to-sit OR sit-stand OR stand-sit OR sit-stand-sit OR sitting-to-standing OR standing-to-sitting OR sitting-standing-sitting) AND (rehabilitation OR train OR regain OR relearn OR recovery OR assist OR support) AND (device OR trainer OR system OR robot OR game).

Inclusion criteria for this focused review were:

1. Systems and devices that are focused on STS training (and functional ability similar to STS, e.g. sit-to-walk),

2. Systems that provided feedback to users.

Exclusion criteria for this focused review were:

1. Systems that were only used for assessments and/or diagnosis (e.g. expert system) with no training aspect,
2. Assistive technologies (e.g. transfer aid) that were not designed specifically to enhance rehabilitation,
3. Prosthetics and orthotics,
4. Non-English Articles.

The search terms and criteria were chosen carefully to include the most-up-date rehabilitation technologies that could be used in training the STS movement in different varieties of illnesses and environments. This was to enable the most complete review of the current literature and patents.

Quality Judgement

It is worth noting that, research on rehabilitation technologies for recovering of the STS movement is not well developed. Although there have been a number of studies in this area looking at recovery of gait and upper limb functions, studies considering the STS movement are scarce. The high-quality studies are those that have:

- Used their systems as part of a randomised controlled trial (RCT) as this research design is considered to be the most rigorous way of determining the treatment effectiveness (see section 6.3),
- Included a large sample size,
- Compared technology supported rehabilitation with conventional rehabilitation.

However, research in using technologies for providing STS training is still young. Only a small number of studies met these quality marks, demonstrating the emerging nature of this research field, consequently, this review will also include studies that focused on the engineering design of STS training technologies (without any clinical evidence).

2.7.2 Results

A total of seventeen papers and articles were identified from the literature search as outlined in figure 3. Papers that do not fit the inclusion criteria or fit the exclusion criteria listed in section 2.7.1 were rejected and not included in this literature review. A checklist developed by Downs and Black, 1998, was then adopted to check against the quality of the found STS studies (see table 1).

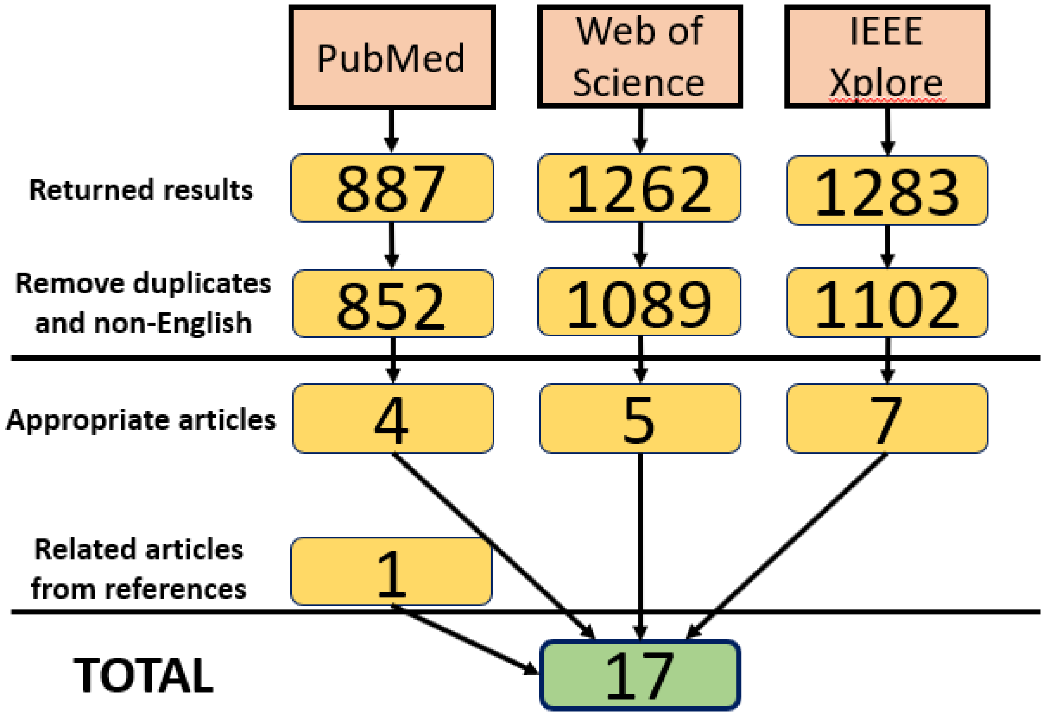


Figure 3: Flow diagram showing the literature search selection and the number of feedback systems for STS training found.

Table 1: A checklist for measuring quality of randomised and non-randomised studies (Downs & Black, 1998) applied to the found 17 STS feedback training systems.

	Checklist criteria (Downs & Black, 1998)																											
Study	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**Total**
(Rosie & Taylor, 2007)	1	1	1	1	1	1	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**23**
(Faria, Silva, & Campilho, 2015)	1	0	1	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**5**
(Kennedy et al., 2011)	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	**7**
(Nakamura et al., 2016)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
(Heiden, Cluff, Richardson, & Balasubramaniam, 2009)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
(Garcia et al., 2015)	1	1	0	1	1	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	0	0	0	0	**14**
(Khotimah, Sholikah, & Hariadi, 2016)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
(Roosink et al., 2015)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
(O’Neil, Craig and Dunlop, Mark D. and Kerr, 2015)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
(Ribeiro, De Sousa, & Viana, 2017)	1	1	1	1	0	1	0	0	0	1	1	1	0	0	0	0	1	1	1	1	1	1	0	0	1	1	1	**17**

(Ramírez, Petrie, Chan, & Signal, 2018)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
(Monticone, Ambrosini, Ferrante, & Colombo, 2013)	1	1	1	1	1	1	0	1	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	0	0	0	1	**18**
(Betker, Desai, Nett, Kapadia, & Szturm, 2007)	1	1	1	1	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0	0	0	0	**9**
(Mak & Hui-Chan, 2004)	1	1	0	1	0	1	0	1	0	1	0	0	1	0	0	0	1	1	1	1	0	1	0	0	0	0	0	**12**
(Stoop et al., 2017)	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	0	0	0	1	0	0	1	1	0	**18**
(Geiger, Allen, Keefe, & Hicks, 2001)	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	1	**13**
(Batavia, Gianutsos, & Kambouris, 1997)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Table 2: Key features of the found 17 STS training systems.

Studies	**Targeted Population**	**Delivery of feedback**	**Use of Virtual Reality**	**Type of feedback**	**When feedback is provided**
(Rosie & Taylor, 2007)	Geriatric population	Visual only	No	KoR on STS repetitions	• Real-time • End
(Faria et al., 2015)	Neurological disorders	Visual and auditory	Yes	KoP on balance and STS progression	• Real-time
(Kennedy et al., 2011)	Neurological disorders	Visual only	No	KoP on weight shifting	• Real-time
(Nakamura et al., 2016)	Rehabilitation patients who struggle to stand independently	Visual only	No	KoP on weight shifting and change of centre of pressure	• Real-time
(Heiden et al., 2009)	Individuals who are training the STS movement	Visual only	No	KoP on angular momentum	• Real-time
(Garcia et al., 2015)	Guillain-Barré population	Visual and auditory	Yes	KoP on weight transfer	• Real-time
(Khotimah et al., 2016)	Stroke population	Visual only	Yes	KoP on maximum height reached when standing-up	• Real-time
(Roosink et al., 2015)	Individuals struggle to stand	Visual and auditory	Yes	KoP on STS progression	• Real-time
(O'Neil, Craig and Dunlop, Mark D. and Kerr, 2015)	Stroke population	Kinaesthetic and auditory	No	KoP on weight shifting	• Real-time
(Ribeiro et al., 2017)	Pregnant population	Visual and auditory	Yes	KoP on balance	• Real-time
(Ramírez et al., 2018)	Stroke population	Visual and auditory	Yes	KoP in STS repetitions	• Real-time

					• End
(Monticone et al., 2013)	Stroke population	Kinaesthetic	No	KoP on speed of standing-up	• Real-time
(Betker et al., 2007)	Neurological disorders	Visual and auditory	No	KoP on centre of pressure	• Real-time
(Mak & Hui-Chan, 2004)	Parkinson’s disease population	Visual and auditory	No	KoP on current head level	• Real-time
(Stoop et al., 2017)	Spinal Cord Injury Population	Visual and auditory	Yes	KoP on general STS performance	• Real-time • End
(Geiger et al., 2001)	Stroke population	Visual	No	KoP on center of gravity	• Real-time
(Batavia et al., 1997)	Stroke Population	Auditory only	No	KoP on centre of pressure	• Real-time

2.7.2.1 Feedback Systems

Feedback systems were identified as technologies that captured kinematic data (e.g. using inertial sensors, force plates, video cameras and strain gauges) while training and used this data to provide automated feedback. Gaming systems, such as the Wii balance board (Nintendo, Kyoto, Japan), Kinect camera (Microsoft, Redmond, Washington, U.S.A.) have been widely adopted in this regard (Mousavi Hondori & Khademi, 2014) (Dos Santos et al., 2015). Commercially available gaming software (i.e. original Wii sport games (Nintendo, Kyoto, Japan) which were designed as home entertainment) might increase physical activity level in healthy adults (Sween et al., 2014), however, evidence of their feasibility and effectiveness in the rehabilitation setting is limited (Clark et al., 2010) (Laufer, Dar, & Kodesh, 2014). Since they are "one-size-fits-all" and designed for individuals with full cognitive and motion capabilities, which many people who are in rehabilitation do not have. The level of difficulty may conceivably be too advanced for many patients. While many of these movement-based games provide feedback on task success, they also include negative feedback which may be demotivating for individuals. Therefore, custom designed systems must be developed specifically for rehabilitation purposes, which are consistent with the understanding of how to deliver extrinsic feedback effectively for error correction and motivation.

The cost of gaming peripherals (e.g. Wii balance board) is significantly cheaper than laboratory-standard equipment for wide-spread adoption. For example, a Kistler AMTI laboratory-grade force plate (Kistler Group, Winterthur, Switzerland) costs $40,000 while a Will balance board costs $80 only. Widely available to buy on the high street shops, these entertainment systems are designed for home-use and occupy less space and are more portable compared to laboratory-standard equipment. Open sourced codes are often provided by the manufacturers for more accessible development, which allows custom developments and greater flexibility such as data collection, program control, data processing and gamification. These clear advantages of home entertainment systems could be translated into the design of rehabilitation systems. It is entirely feasible that the real-time kinematic data captured from these peripherals can be used to generate appropriate feedback for training the STS movement.

A good example of this is the WeHab system (Kennedy et al., 2011), which was designed specifically for stroke survivors, using a commercially available Wii balance board to measure force-symmetry shifting during STS transitions. The system provided real-time knowledge of performance. The visual feedback showed an actual Wii board on a screen from a bird’s eye view. A live green pointer displayed over the board and tracked the variation in CoP with a red tail displaying past readings. A separate window with two bar charts demonstrated the percentage of force-symmetry loading on each leg when standing. A pilot study was conducted on five neurologically damaged patients as they practised with the system throughout their rehabilitation. All participants saw their STS, force-symmetry loading and stepping performance improved as measured by the functional independence measure scale (from 5 points to 16 points after eight training sessions) (Kennedy et al., 2011).

The Balance Visualisation System (Nakamura et al., 2016), which was also aimed for stroke survivors, provided a similar feedback interface as the WeHab system. This system consisted of three Wii boards. Two boards were placed on the ground for measuring CoP applied by both feet. Another board was placed on the seat pan so that it could measure the CoP when sitting and recording the moment the body left the chair (seat-off). Knowledge of performance was provided. The real-time CoP data were provided as dots on the left-hand side of the screen. Blue and pink lines were drawn to enclose the dots. These represented the maximum and minimum change in the CoP locations. The right-hand side of the screen displayed feedback on completion (i.e. conclusive feedback), filtered and unfiltered ground-reaction force (GRF) applied on each foot when standing up. At the end of an STS transfer, a line was created to show the average values at an individual time. The system did not test on patients, but thirty-nine therapists were invited to comment on it. The participants were pleased to see the system had the capability to acquire multiple biomechanical parameters, but they mentioned it could be difficult for patients wishing to carry out their own rehabilitation activities (Nakamura et al., 2016).

Rehab@home system (Faria et al., 2015) was also developed for stroke survivors, again using the Wii balance board, in this case, two of them were used. One was placed on a chair to measure CoP while seated and one was placed under the feet. This system also includes a webcam to capture motion data using an optical flow algorithm to obtain head trajectory. The webcam also took the graphical image of the user when standing up so that the resulting video clip could be replayed afterwards for visual feedback. Very similar to the WeHab system, visualisation of the Wii balance boards was demonstrated in the feedback interface as well for tracking CoP. Graphical plots of the GRF measured by each sensor on each Wii balance board were displayed on the right-hand side of the feedback interface. Other than this, the system only provided auditory feedback on force-symmetry loading (e.g. "Move your trunk to the left/right"). A usability test was conducted on seven brain-injured patients. The feedback from them suggested the system was user-friendly and attractive. However, the small texts were difficult to read, and the auditory feedback was not loud enough.

Heiden and colleagues (2009) developed a real-time feedback system in training the STS movement (Heiden et al., 2009). The movement was captured with a ten-camera motion capture system and a force plate. Users had to wear distinctive reflective markers on their body. By tracking real-time STS movements, the system calculated CoP, hip and ankle joint angles and the body's CoM angular momentum. Visual feedback was provided as a green bar in tracking the completion of the STS movement. Moreover, there was a line graph representing the CoM angular momentum. The system has not so far been tested by mobility impaired individuals but demonstrated the scope of what could be achieved for STS feedback.

2.7.2.2 Virtual Reality

Researchers have used virtual reality (VR) technologies for several years now to simulate real-life situations. Geriatric patients have been reported to find VR more enjoyable than standard therapy (Molina, Ricci, De Moraes, & Perracini, 2014). As a result, VR has the potential to improve patient's motivation and attention (Liebermann, Buchman, & Franks, 2006). The number of movement repetitions completed, time dedicated to therapy and patient's engagement with rehabilitation programs have all been found to be higher when practised under VR (Rand, Givon, Zeilig, Nota, & Weingarden, 2012).

For instance, Khotimah et al. (2015) developed a sitting-to-standing-to-walk VR system. The system was using Kinect technology (Microsoft, Redmond, Washington, U.S.A.) integrated with a computer-based application to provide training for individuals with physical impairments. The system displayed the graphical images captured by the Kinect camera in real-time and presented as mirror images. The display showed the actual room and the user as they trained. An artificial object then appeared above the person, for ten seconds, as a target to be reached for standing up. The system provided different degrees of difficulty. If the user reached the target within a set time limit, the height and distance of the displayed object would then increase and vice versa

(Khotimah et al., 2016). A score was provided at the end of training. An experiment was carried out on two healthy older adults and a stroke survivor. It was found the system was safe to use and participants found it helpful.

Another VR system that provided a mirror image of the user was developed for training the STS movement in older adults by integrating motion capture and projection technology (Roosink et al., 2015). Users had forty-one reflective markers attached to their body and then sat in the middle of a motion capture laboratory. A carton avatar tracking the real-time full-body movement of the user was projected on a wall. The VR system had pre-defined three trunk flexion angles (15, 25 and 35 degrees) that the user must reach when standing up for the training program to proceed. Once the user reached these angles, a visual signal showed as “OK” will be displayed on the wall along with a bell ringing sound. The system was tested on healthy participants regarding its technical implementation.

2.8 Discussion

Research on rehabilitation technologies designed to enhance STS training have shown that providing automated feedback, particularly visual feedback with mirror images, while training could improve outcomes (McCabe, Haigh, & Blake, 2008) (Ramachandran & Altschuler, 2009) (Hung, Li, Yiu, & Fong, 2015) (In, Cha, Jung, & Jung, 2016). This success could relate to the hypothesis that visual images are more likely to be remembered than words in both short-term and long-term memory (Whitehouse, Maybery, & Durkin, 2006).

This could explain the result of a trial conducted on the GrandStand STS training system (Rosie & Taylor, 2007). The system provided real-time feedback and conclusive feedback at the end of training. Sixty-six older adults aged above eighty were involved in the trial and participants who trained with the system were found to have statistically significant (P = 0.001) improvement in their functional movements as measured by the Berg Balance Scale (Rosie & Taylor, 2007).

Visual feedback could also be delivered qualitatively or quantitatively. This would allow users to “see” their performance from their own perception with their eyes and trigger cognitive responses to initiate movements (Noble, Eng, & Boyd, 2015). The STS feedback systems reviewed were found to have several shortcomings. Most of the systems, such as the WeHab and Rehab@home, focuses on force-symmetry only. However, as discussed in section 2.4, while force-symmetry is an important factor, trunk forward lean and impulse generation for push when rising are also important for a successful STS transfer. However, only one VR system, developed by Rooskin et al (2015), was found to provide this range of feedback on these variables. Most feedback systems could not automatically analyse the performance and simply relied on healthcare professionals to interpret the data as no textual or auditory feedback generated to users (for example, the Balance Visualisation System). Therefore, if these systems were implemented for self-use, the users must have a reasonable knowledge of movement analysis and intact cognition for interpreting their performance from what could be complex graphs and numerical outputs. This is likely to pose great difficulty for some patient groups and increase the resources needed if implemented in a clinical setting.

Some of the systems, such as the WeHab did not provide conclusive feedback or any other guidance on future improvement. Therefore, they might not be suitable for use independently at home or in a clinical environment without the presence of a therapist. If feedback for future improvement could be provided along the lines of what is typically offered by professional rehabilitation staff, including advice for future improvement based on previous performance, this could potentially ease users' understanding of the provided mathematical data. Moreover, the found VR systems did not exploit the full potential of VRs, such as simulating a real-time situation (e.g. a park, public transport or home) which are known to improve engagement and motivation (Green & Wilson, 2012).

One major flaw in all this research is that the lack of evidence of feasibility, acceptability and effectiveness. These studies are weak with several participants tested on them with the authors. Moreover, there is a lack of control comparison, such as conducting a randomised controlled trial in a clinical setting. Also, there is a lack of evidence that stakeholders were engaged in the design process. In fact, the user-friendliness of the found systems can be improved in different aspects. Firstly, several systems, WeHab, BVS and Heiden’s (2009), did not provide audio support. This could pose a barrier for users with visual impairments. Readability of text-based feedback was also found to be an issue with Rehab@home as the texts were too small for users with poor eye sights. Not to mention inadequate feedback on future performance was provided.

Considering these limitations of current systems, the following design criteria were proposed for developing a new STS feedback training system:

- Include a use of VR environment to increase motivation and engagement,
- Provide instructions for executing a successful STS transfer,
- Provide real-time feedback and conclusive feedback for future improvement with knowledge of results and knowledge of performance,
- The frequency of providing feedback should be flexible and should avoid feedback on every repetition,
- The provided feedback should be interpretable by all users with or without the presence of a therapist,
- Light and portable electronic equipment will be adopted to enhance translation to home use and various clinical environments.

These design criteria form a strong foundation for the total design framework. The findings began “the market” stage of the total design framework as suitable scopes and boundaries were able to be defined from limitless design options. Also, these criteria will be applied to the user-centre design study, for example, writing appropriate questions for the questionnaires, preparing interviewing questions and concept generation.

2.9 Summary

Being able to stand-up independently is critical to achieving activities of daily living. This chapter explored the biomechanics of the STS movement and identified its four transitional phases (flexion-momentum phase, momentum-transfer phase, extension phase and stabilisation phase), from sitting to standing. The difficulties older adults experience when executing this movement were also discussed, including poor force-symmetry control, a lack of impulse generated when rising and a lack of forward trunk movement.

Optimal STS performance can be regained through physical rehabilitation using technology. The use of active and passive mechanical devices in regaining various functional movements (such as upper limb functions and gait) were discussed. However, there is a lack of evidence that they are superior to traditional hand-on manual rehabilitation.

The provision of feedback has been demonstrated as the key to motor relearning. Therefore, this chapter analysed the use of intrinsic and two different forms of extrinsic feedback (i.e. knowledge of results and knowledge of performance) in motor relearning. The effects of varying frequency of the provision of feedback and delivering positive and negative feedback were discussed. A literature search was carried out on feedback technologies for training the STS movement. The barriers and opportunities of the found technologies, including VR technology, were exploited in this study and a list of design criteria were proposed for developing a new STS feedback training system.

Chapter 3: User Centred Design Study

3.1 Introduction

Technology may offer solutions to increase the opportunity for safe and repetitive rehabilitation practice without an increased burden on funded services by assisting healthcare professionals in a clinical environment and promote self-management at homes. There has been empirical research achieved in the fields of rehabilitation devices demonstrating effectiveness, but adoption is slow and only a small percentage of developed technologies are ever translated into routine clinical practice (A.-M. Hughes et al., 2014) (Connell, McMahon, Watkins, & Eng, 2014). A likely reason for this poor engagement with technology is the lack of user involvement in the traditional design process which excludes stakeholders from the design process and only involves the users in the evaluation stage (Egglestone et al., 2009). In order to produce a highly usable and accessible rehabilitation system with the potential to translate to routine practice, it is considered important to recognise user needs and requirements at the beginning of the process while identifying negative issues that risk poor adoption. This has been termed “User Centred Design” (UCD) (Devi, Sen, & Hemachandran, 2012).

This chapter presents a UCD process for the development of a feedback system for recovering the STS movement. It focuses on the evidence used to identify stakeholder preferences and user recommendations of such a device, to produce a design specification from limitless design options and possibilities.

The chapter will include details of numerous user generated concepts and conclude with the selection of the final concept for prototyping which was achieved through stakeholder consensus.

3.2 User-Centred Design Process

The intention of this study was to identify the design features of greatest interest to stakeholders of a feedback system that optimises training of the STS movement in mobility-impaired older adults which could be delivered within a clinical environment. This was achieved in three stages, see figure 4 for an overview. Ethics approval for the study was obtained from the University of Strathclyde, Biomedical Engineering Departmental Ethics Committee (Reference: Paper DEC.BioMed.2014.41).

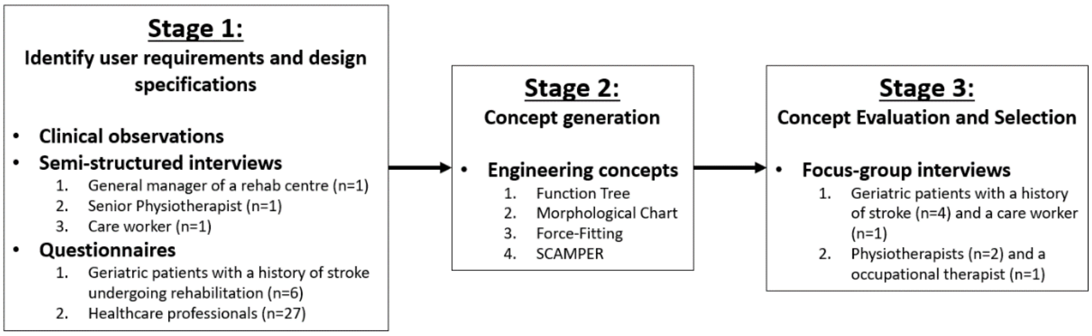


Figure 4: The User Centred Design process adopted in this study.

3.2.1 Stage 1: Identify User Requirements and Gather Initial Design Specifications

Methods: Observations, interviews and surveys on the way rehabilitation technologies are being used currently.

3.2.1.1 Observations - Methods

Clinical observations of user interaction with rehabilitation technology were conducted to identify the equipment currently used in the clinical environment and better understand how technology is used practically in rehabilitation. A total of six observational sessions, one hour each, were undertaken to understand end-user needs, therapist workflow, provision of feedback and physical environment at a rehabilitation centre. The observed sessions consisted of users carrying out independent practice with mechanical and computerised equipment and exercises supervised, but not physically assisted, by therapists. With permission from participants, detailed written notes and photographs of equipment were taken for analysis. The POEMS (People, Objects, Environments, Messages and Services) framework, which was developed for examining video observations of user interactions in design projects (Whitney & Kumar, 2003), was used in this study to categorise and analyse these observations.

3.2.1.2 Observations – Intermediary Results

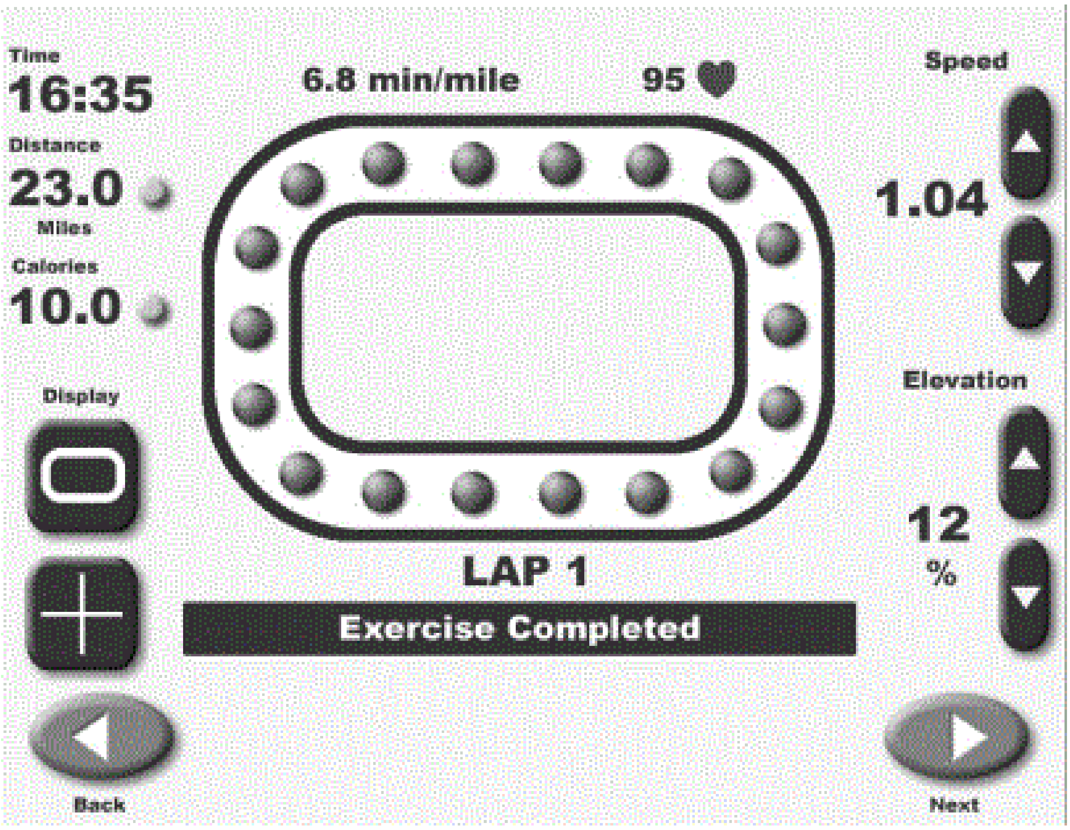
The following general observations were recorded:

- Upper limbs were used for support when standing-up and standing still,
- The stronger side was used preferentially during most activities,
- Few instructions or guidelines were provided by the systems, necessitating frequent interactions with the supervising therapists,
- Tactile, verbal and visual cues were provided by therapists to the patients for instructing their clients to execute certain motions.

Observations Concerning Computer Generated Feedback

Automated real-time visual feedback was provided by a gait training system (shown in figure 5) with additional automated conclusive feedback presented at the end of the sessions which was based on numerical data and charts (shown in figure 6).

The performance data had to be interpreted by therapists in the absence of guidance from the device and could not be easily understood by patients. Another system was based on a menu-driven interface, which the therapists struggled to navigate and could only select the same options for all users with different needs. Therapists spent 45 minutes per gait training session assisting individuals onto a treadmill, depriving the other patients of their attention.



Time
16:35

Distance
23.0
Miles

Calories
10.0

6.8 min/mile

95

Speed
1.04

Elevation
12
%

LAP 1

Exercise Completed

Figure 5: An exercise track displayed in real-time on a gait training system.

Exercise Results

Name:

Date: 11/26/2014 11:22 PM

Time: 6:00 Steps: 415 Avg Speed: 1.4 MPH Distance: 225 meters

Average Walking Speed: 0.62 meters/sec

Average Step Cycle: 0.58 (cycles/sec)

Average Step Length: Left: 55 cm

Right: 61 cm

Coefficient of Variation: Left: 7 %

Right: 5 %

Time on Each Foot: Left: 50 %

Right: 50 %

Ambulation Index Result: 79

Figure 6: Feedback on performance was provided by a visual feedback system (Biodex, Shirley, New York) in the rehabilitation centre.

Figure 7: A power-assisted mechanical machine in the rehabilitation centre.

Identified Ergonomic Issues

Multiple ergonomic issues associated with power-assisted mechanical equipment in the rehabilitation unit (see figure 7) were identified:

- Users were unable to grasp the one-sided control panel and couldn't operate the small push-buttons with their weaker side,
- One patient was incapable of reaching the handles which were not adjustable in length,
- Safety rails and handles frequently restricted wheelchair access,
- Some systems had no physical barriers around the patient which caused safety concerns for some patients,
- The timer, which could only be set by the therapists, created extra workload for the staff while patients were waiting,
- A warning beeping sound to signal the start of a session was produced by several machines simultaneously and appeared to confuse therapists trying to provide individual attention,
- No extrinsic feedback was provided by these systems at all.

3.2.1.3 Individual Interviews - Methods

Semi-structured individual interviews, using a naturalistic inquiry approach (Alshenqeeti, 2014), were conducted to understand end-user's experience of rehabilitation, needs of feedback and identify influencing design factors based on their preferences. Users were recruited from the same rehabilitation centre where the observational sessions were conducted. Initially, individual interviews were achieved with three representative stakeholders at the centre:

1. The general manager with responsibility for procurement,
2. A senior physiotherapist,
3. A care worker directly responsible for assisting users with rehabilitation technology.

3.2.1.4 Individual Interviews – Intermediary Results

All interview participants agreed that the current rehabilitation services are inadequate for their patients. The physiotherapist suggested that the widely used, traditional approach of delivering physical rehabilitation, which requires constant manual hands-on support, was "unsustainable" as they worked under-pressure with limited resources. They believed the introduction of home-based rehabilitation systems would provide more opportunities for practice and "not limited to travelling, time restriction or the weather". Nevertheless, concerns were raised regarding safety, fear and risk of injury when practising at home independently. The physiotherapist emphasised that no patients could exercise at a clinic without staff supervision. Clinical evidence was the first and foremost consideration factor when purchasing rehabilitation systems suggested by the manager and therapist. The manager expected the cost of an STS feedback training system to be under £5000, including once-a-year maintenance for its lifetime, which was anticipated to be around fifteen years.

The current equipment in the centre was generally praised for having a “quick-to-learn” and “easy-to-use” interface as most of the users could operate them “after a single demonstration”. However, some criticism was directed at the passive nature of the devices (i.e. all movements were mechanically supported by the systems). They could not detect obstacles within its range of motion, a problem which had previously caused physical injury to a therapist. Poor wheelchair access was mentioned by the care worker who had “reduced her working hours” due to a repetitive injury caused by heavy lifting of patients and equipment. Another problem raised was the lack of indications of performance being provided which would “help for both the patients and physiotherapists”. The therapists “had no idea of user’s progress” until the annual review assessment was conducted which involved “testing different ranges of muscle movement for power, range and speed, STS performance, gait performance, upper-limbs movements and cognitive assessment”. When asked for which types of systems shall be developed for training the STS movement, all users are interested in the use of computerised technology in providing visual feedback when relearning the movement.

3.2.1.5 Surveys - Methods

Two questionnaires, one for geriatric patients with a history of stroke and one for therapists, were developed (see appendix 2) to gather information that would outline the rich landscape of user experience and evaluate stakeholders' acceptance of potential design factors. The survey administration was informed by literature on questionnaire design (Murray, 1999) (O'Cathain & Thomas, 2004) (Bowling, 2005). Draft versions were developed and reviewed by a clinical physiotherapist and a care worker to ensure the questions included all aspects of STS rehabilitation and that the questions were understandable, and the questionnaires could be fully completed easily and within a reasonable timeframe. Participants were asked a series of open-ended questions for assessing their overall experience and attitude towards the current practice of STS training. Moreover, response options of user preferences for numerous design factors were rated on a five-point Likert scale from "non-relevant (1)" to "most important (5)". The questionnaire developed for the patients was reduced in length after a review. Instead of providing the Likert-scale questions, participants were asked for their preferences for a futuristic STS training system by an open-ended question. The results were then ranked in an ascending order. Demographic information was captured for all participants.

The questionnaire for therapists was emailed across Scotland through Chest, Heart, Stroke Scotland to their members. A participant information sheet outlining the nature of the research was attached for all participants (see appendix 1). Patients were recruited from a rehabilitation centre. As the patient participants may have visual impairments, problems with upper-limb functions and/or cognitive issues which might pose difficulties for questionnaire completion, the researcher visited these participants in person to support questionnaire completion.

Data from the two questionnaires were analysed using IMB SPSS statistics, version 21.0 (IBM Corp, Armonk, New York, U.S.A.). Frequency distributions were generated for close-ended and multiple-choice questions to demonstrate the distribution of the collected quantitative data. Not all participants fully completed the questionnaires so the percentage of responses to individual questions was calculated based on the total number of respondents for the specific question. The analysed responses from the questionnaires were used to develop the product design specifications (PDS) (see appendix 3.1) for the rehabilitation system.

3.2.1.6 Surveys – Intermediary Results

A total of 27 therapists completed the survey. Data from five of the participants were excluded as they had no experience of providing STS training (see table 3). Six geriatric patients with a history of stroke recruited from a rehabilitation centre completed the questionnaire with the researcher (see table 4). The analysed quantitative and qualitative results will be presented in this section.

The results, which identified a visual feedback system is essential for STS training, contributed to the development of the questionnaires.

Table 3: Demographic and profile of the therapists involved in the questionnaire stage.

	Response Categories	**Responses**	
		n	**%**
Gender	Female	27	100
	Male	0	0
Professional role	Physiotherapist	12	44.4
	Occupational Therapist	9	33.3
	Speech and Language Therapist	3	11.1
	Prosthetist / Orthotist	1	3.7
	Others	2	7.4
Years of experience	>0 to <5	1	3.7
	>=5 to <10	5	18.5
	>=10 to <15	6	22.2
	>=15 to <20	3	11.1
	>=20 to <25	4	14.8
	>=25 to <30	3	11.1
	>=30	5	18.5
Deliver STS training	Yes	22	81.5
	No	5	18.5

Table 4: Demographic and profile of the geriatric patients with a history of stroke involved in the questionnaire stage.

	Response Categories	**Responses**	
		n	**%**
Gender	Female	1	16.7
	Male	5	83.3
Years of rehabilitation	< 1	2	33.3
	>=1 to <2	2	33.3
	>=2	2	33.3
Frequency of visit per week	1	1	16.7
	2	0	0
	3	4	66.7
	4	1	16.7
	5	0	0
Received STS training	Yes	6	100
	No	0	0

Experience and Approach to Sit-to-Stand Training

When therapists were asked about their approach to training the STS movement, 81.2% of them were using mechanical assistance (e.g. hoist, Stedy's frame, pressure mat, ejector chair and plinths) with the aim of promoting force-symmetry control, leg and trunk coordination during the movement. They believed that the use of equipment could allow patients with "poor functional physical ability to practice", "increase a patient's confidence" and "prevent risks and injuries to patients and colleagues".

Another reason for using equipment was to reduce fatigue and allow more opportunity for practising in a consistence manner. Equipment that could be self-operated by patients was considered positively by the patients as it helped them gain confidence. However, manual hands-on support must be provided at all time to ensure safety.

However, three therapists mentioned that some of the current equipment was not fit for all size of users and difficult to use for patients with little functional movement. Usage of computerised rehabilitation systems was not mentioned by any participants.

With regards to advantages of their current practice, 17 out 27 therapists mentioned that it was "functional, practical and person-centred" and the treatment plan had “no fixed set pattern”, “easily broken down and tailored to more adaptable components” while it could be easily demonstrated and discussed. The remaining 10 therapists did not comment on their current practice.

Feedback on performance could also be provided manually in real-time and “not just at the final finishing position”. Seven therapists criticised that it was “resource dependent” (e.g. staff, time and intensity). The majority (72.3%) suggested manual therapeutic handling, which often “required multiple staff in assisting patients”, in rehabilitation therapy continued to be the tradition but was hard to deliver frequently enough. All groups of stakeholders illustrated issues around the availability of therapeutic resources (i.e. limited access to therapists and no support outside therapy sessions) and the negative impacts on patients, especially for outpatients.

Many therapists believed that the success of STS training was dependent on “patients’ motivation and ability” and was challenging for individuals who had “little engagement” and “lack of confidence” even with the use of equipment. It was challenging for all “staff and carers to follow the same technique” which impacted long-term effectiveness. All therapists responded that verbal feedback was the primary method of providing feedback, including knowledge of performance and knowledge of results for “affirmation and suggestion for improvement”. This point was emphasised by all the patients who criticised the lack of indications of performance and poor progress records. Seventeen therapists also provided visual feedback and three respondents also delivered sensory feedback, such as tapping on the backside. Three suggestions were obtained from therapists against the usefulness of written feedback. With regards to ensuring patient's safety, thirteen therapists advocated that regular physical assessments are required to understand patient's mobility functions, for example, the STS movement.

Rating Design Factors by Therapists

As discussed in section 2.8, feedback is key to motor relearning and technology has the potential to improve rehabilitation outcomes by providing this feedback. Therefore, participants were asked to rate the most important design factors of a feedback interface, i.e. the interaction between the users and the technology. For training the STS movement, therapists put supporting individuals with disability, such as cognitive and communication impairments like aphasia, as the top reason. This was followed, in ranked order, by promoting motivation, providing a user-friendly interface, delivering real-time feedback, educating the patients, providing conclusive feedback at the end of training and contains real-life stimuli as detailed in figure 8.

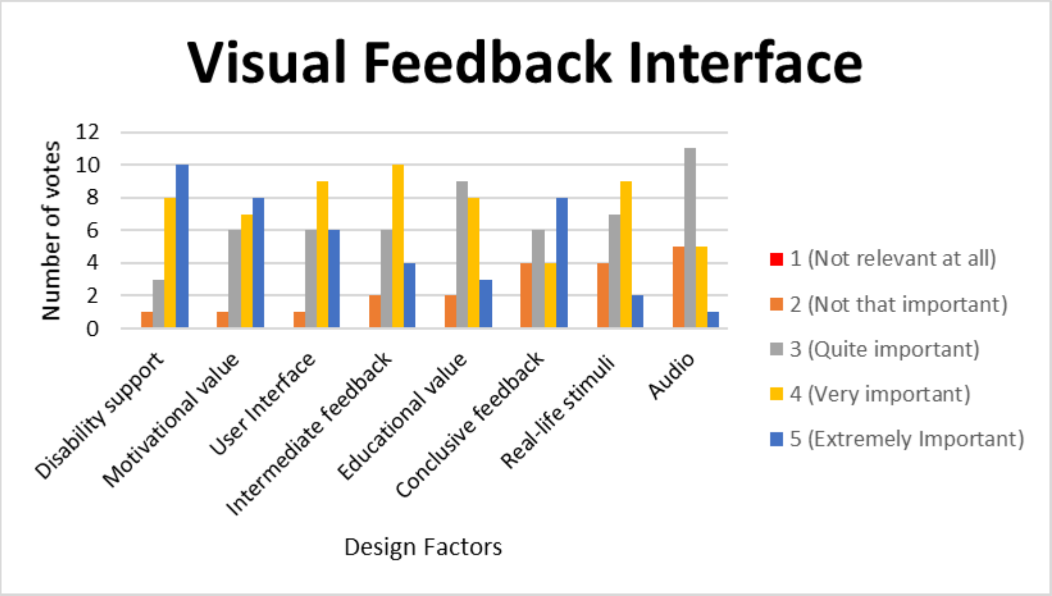


Figure 8: Breakdown of responses on therapists' perceptions of a visual feedback interface for STS training.

3.2.2.1 Stage 2: Concept Generation - Methods

Several conceptual design tools were used for generating broad concepts based on the PDS developed in stage 1. These engineering ideas were generated to address different aspects of the identified needs.

A function-means tree (see figure 9), which is widely used for functional analysis in product development (Alshenqeeti, 2014), was developed to generate solutions for the functions and requirements defined in the PDS in a hierarchical presentation. The "tree" started from the root node (primary function) and progressed down to leaf nodes (defined solutions) by solution paths which were pruned continually based upon evaluation with different criteria and constraints. The defined solutions, such as "user motion/force sensors” and “emergency notification” then were defined in a morphological chart.

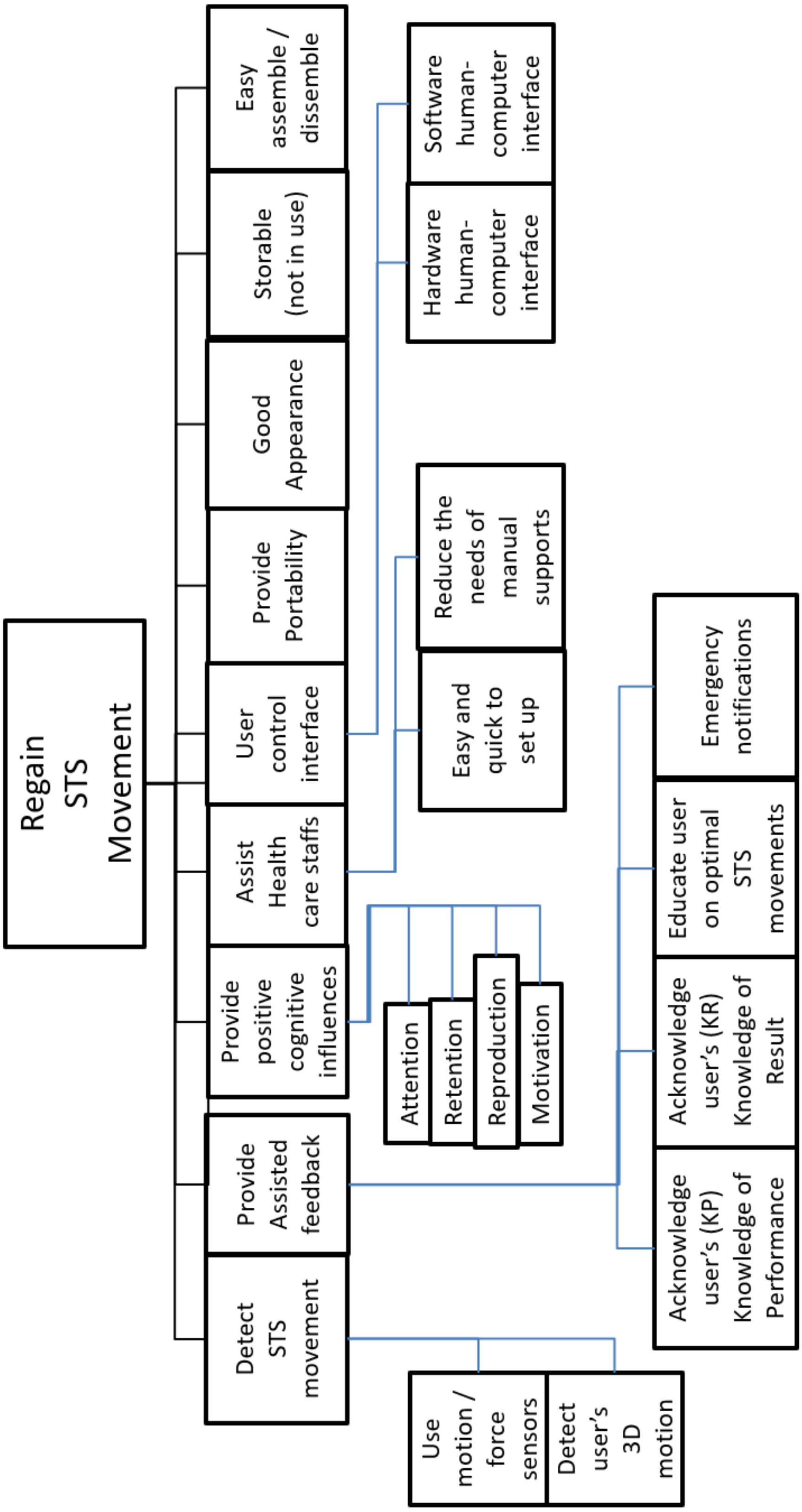


Figure 9: The function-mean tree generated for functional analysis of a STS training system

A morphological chart (see figure 10) was then generated to create combinatorial solutions based on the functions defined on the “tree” for exploring the design space. By using a branch-and-bound search strategy, different solutions were selected from each category to create concepts for the overall STS feedback training system. They included the best, worst and random solutions in the researchers’ point of view based on the PDS to reflect the most feasible and impractical designs for this project within the scopes of time and budget (Huang & Mak, 1999).

Figure 10: The morphological chart generated to create combinatorial solutions.

Concept Features	**1**	**2**	**3**	**4**	**5**
Acknowledge user's KP (Knowledge of performance)	Avatar tracking user's STS movements (Visual feedback)	On-screen quantitative representation and qualitative messages	Produce vibration relative to performance	Sound (piano pitch)	Colour metric score for performance
Acknowledge user's KR (Knowledge of results)	Messages on relevant movement cues	Quantitative Score on goals	Happy face / Sad face on goals	Graphs on magnitude of the errors	Praise of results
Educate user on optimal STS movements	Actual person/anime demonstration	Verbal instructions	Symbolic stimuli (e.g. movies, TV, literature)	(EMG) Electromyography motor rehearsal	
Emergency notifications	Buzzing Alarm	LED lights	Flashing screen	Vibration	Smoke
Hardware User control interface	Hand controls	Foot controls	Eyes controls	Breath controls	Gesture controls
Software User control interface	GUI Icons	Commands line interface (CLI)	Pull-down menu		
Attention (Notice taken of sensory stimuli)	Selective attention (e.g. only focus on one performance)	Visual attention (e.g. highlighted, zoom, blur)	Divided attention (e.g. simultaneous visual + auditory)	Simultaneous Attention (e.g. focus on all types of performance)	
Retention (Convert sensory stimuli into symbolic code)	Cognitive elaborative rehearsal	Generation effect (e.g. creation of your own knowledge)	Dual coding (e.g. create visual and verbal memory on your own)	Distributed effort (e.g. spread out, rather than conclude)	State & context dependent (e.g. environment)
Reproduction (Symbolic code results in behaviour)	Physical Capability	Self-Observation	Feedback		
Motivation (Theoretical constructs explain behaviour)	Extrinsic motivation (e.g. external reward)	Intrinsic motivation (e.g. originates inside)	Vicarious motivation (e.g. behaviour of others)	Reinforced (e.g. being told to do so without a reason)	
Use motion/force sensors	Straps	Harness	Double sided tape	Propulsion system	Safety pins
Easy and quick to set up	Zipper	Hook-and-Loop fastener	Buttons and buttonholes	Snap	Hook-and-Eye closure

In order to create extra ideas which were unique, unusual and highly original but might still be suitable for development, a creative brainstorming force-fitting technique (Treffinger & Isaksen, 2005) was used. The method involved combining random, unrelated and unconnected objects (i.e. a ladybird toy car, a CD case, a cloth peg, a bubble wand, a staple remover, a cleaning sponge and a bracelet) to obtain new perspectives and viewpoints that might unexpected aroused and viable for the new STS training system. All the developed concepts underwent refinements through SCAMPER (Eberle, 1996) which is a critical thinking technique based on substituting, combining, adapting, modifying, putting to another use and eliminating individual components of the existing concepts (see appendix 3.6). These novel systematic creative techniques were tested and shown to enhance design ability in a variety of settings including product design (Yazar Soyadı, 2016).

3.2.2.2 Stage 2: Concept Generation – Intermediary Results

Multiple concepts for the presentation of real-time feedback, conclusive feedback and portable wearing technology were developed during this concept generation stage using several concept generation tools mentioned in section 3.2.2.1. They were developed from stakeholders' feedback in stage 1. These concepts are explained in the following sections.

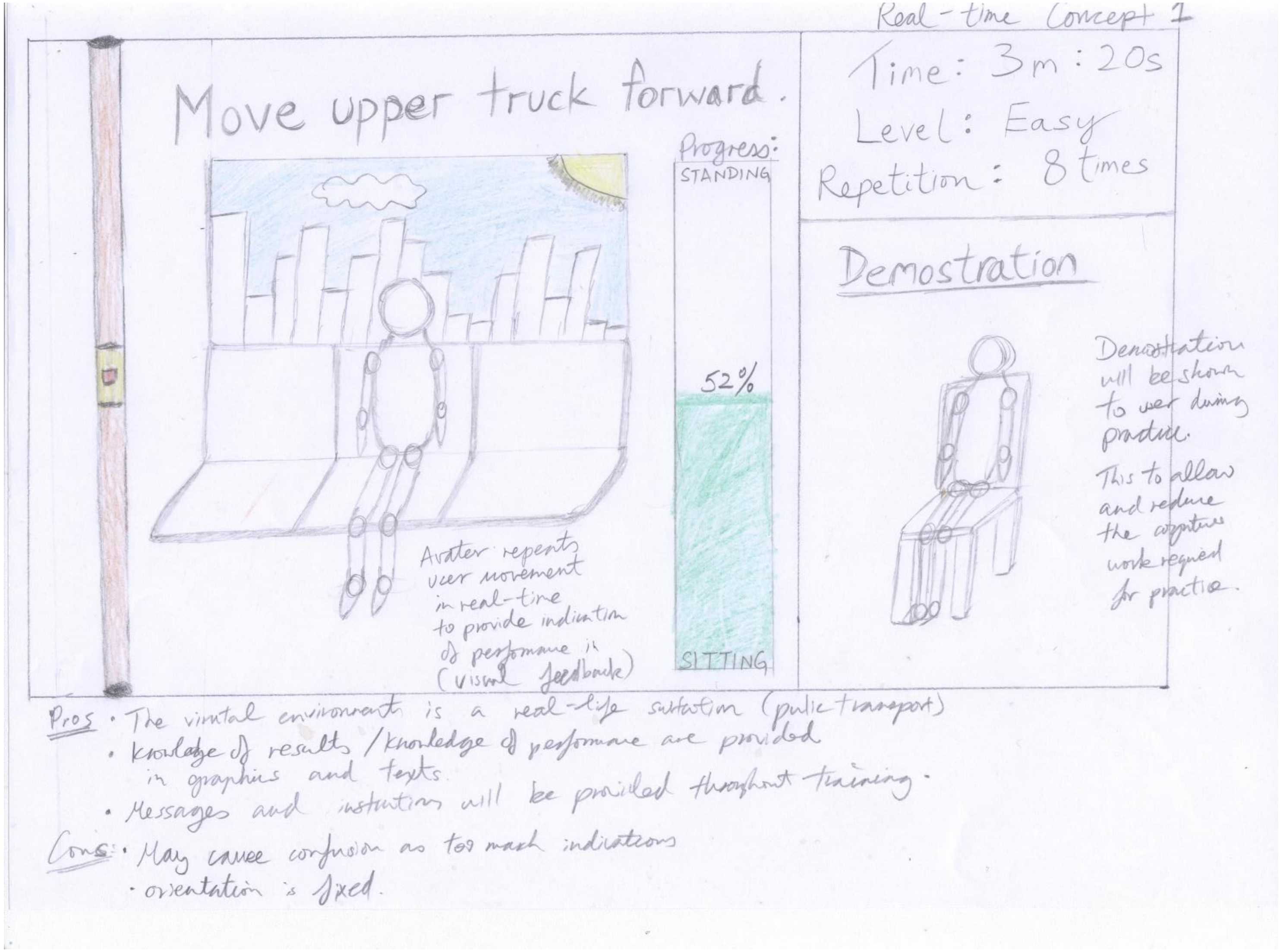
A) Real-Time Feedback Presentation

The first concept demonstrated a virtual reality (VR) environment based on a "bus" (see figure 11). By providing computerised automated feedback, it reduces the constant needs for staff inputs on patient's performance and the VR simulates real-life stimuli and potentially increase motivational value.

The key elements of this concept were:

- An avatar provides a graphical representation of the user's body. This mimics the user's movements so that real-time "mirror" feedback on movements can be provided visually,
- A bus environment (window, seat, handle, LED display board and objects outside the window). This "bus" replicates an important form of public transport which many patient participants were concerned about falling when travelling to shopping and leisure activities,
- Instructions and feedback on performance delivered in audio and texts for users with visual or hearing impairments,
- The number of successfully completed movements and a timer provided in texts to notify the current status,
- A horizontal bar chart to show the completion of an STS execution.

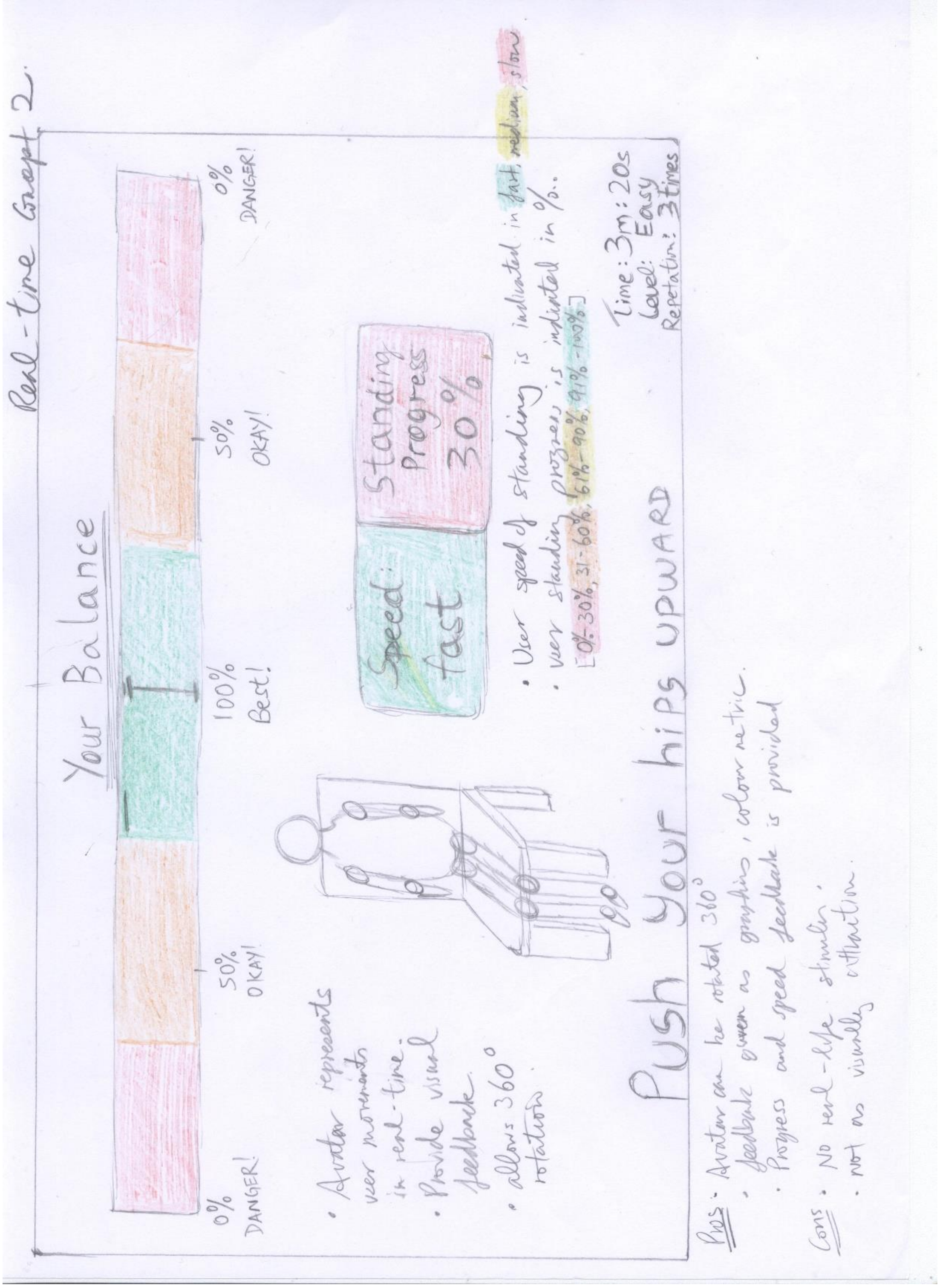
Figure 11: The first real-time feedback presentation concept demonstrated a virtual reality (VR) environment based on a "bus".



The second concept provided an avatar with a plain background (see figure 12):

- The absence of the VR to improve focus,
- More textual feedback (subtitles, such as “push harder with your left leg”) is provided to clarify STS instructions,
- More feedback on performance in colour, texts, numbers and charts (force-symmetry, speed and progress) to attract user attention,
- Use of coloured bar charts which are clearly numbered and marked with the interpretation of performance (best, okay and danger), to indicate force-symmetry,
- The use of colour is extensive (from green to red), similar to the traffic light system.

Figure 12: The second real-time feedback presentation concept provided an avatar with a plain background.

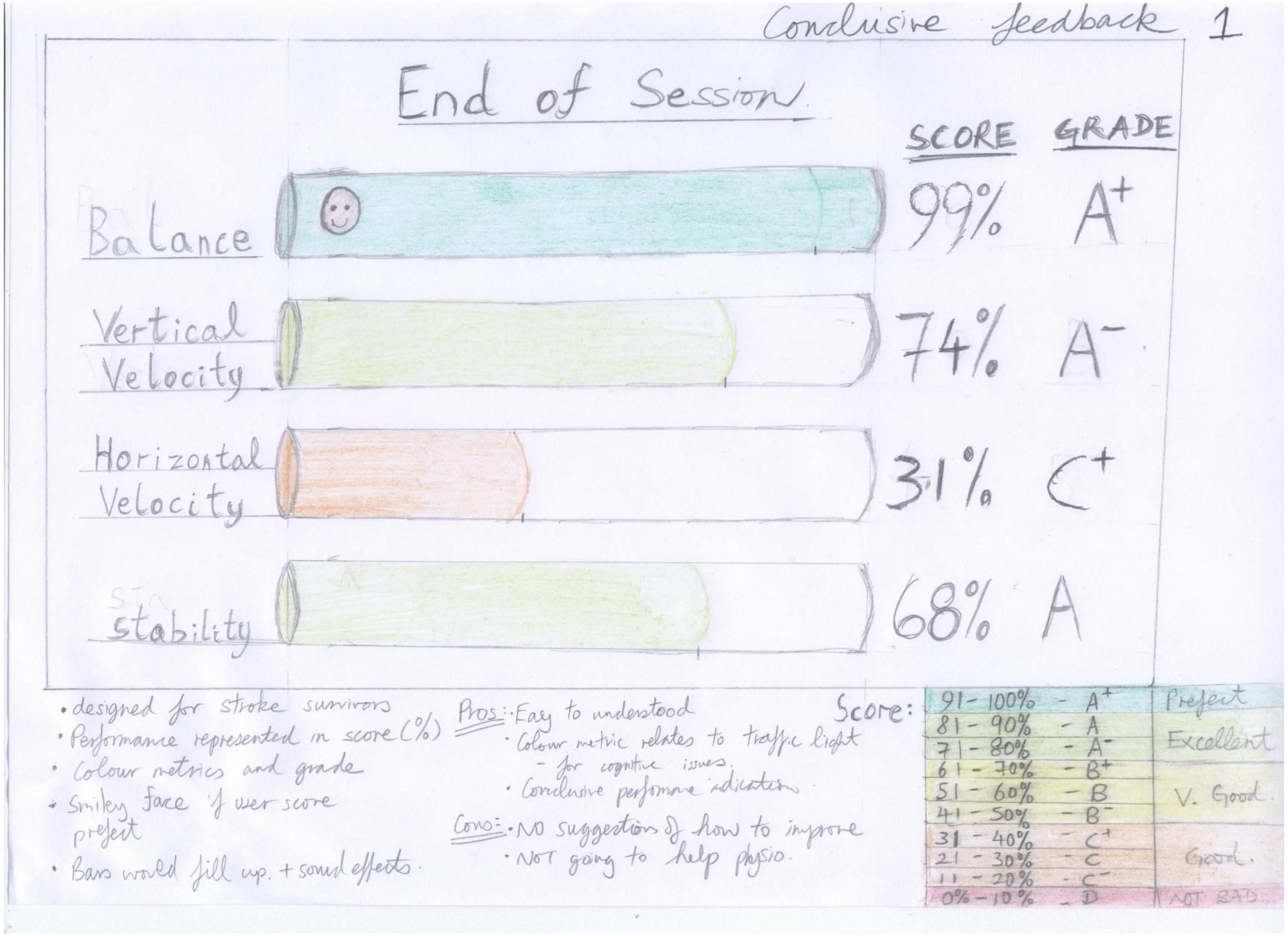


B) Conclusive Feedback Presentation

The first concept showed bar charts were used to indicate performance at the end of each session (i.e. conclusive feedback) (see figure 13):

- Feedback provided was related to force-symmetry, vertical velocity and trunk forward lean,
- Bars are filled based on percentages of scores and coloured from green to red based on performance for easy interpretation,
- Scores are in percentages and grades are provided for each category of performance,
- Use of emojis, for example, a happy face for success, a sad face for failure.

Figure 13: The first conclusive feedback concept showed bar charts were used to indicate performance.



- designed for stroke survivors
- Performance represented in score (%)
- Colour metrics and grade
- Smiley face if user score prefect
- Bars would fill up. + sound effects.

Pros: Easy to understood
- Colour metric relates to traffic light
  - for cognitive issues.
- Conclusive performance indication

Cons: NO suggestions of how to improve
- NOT going to help physio.

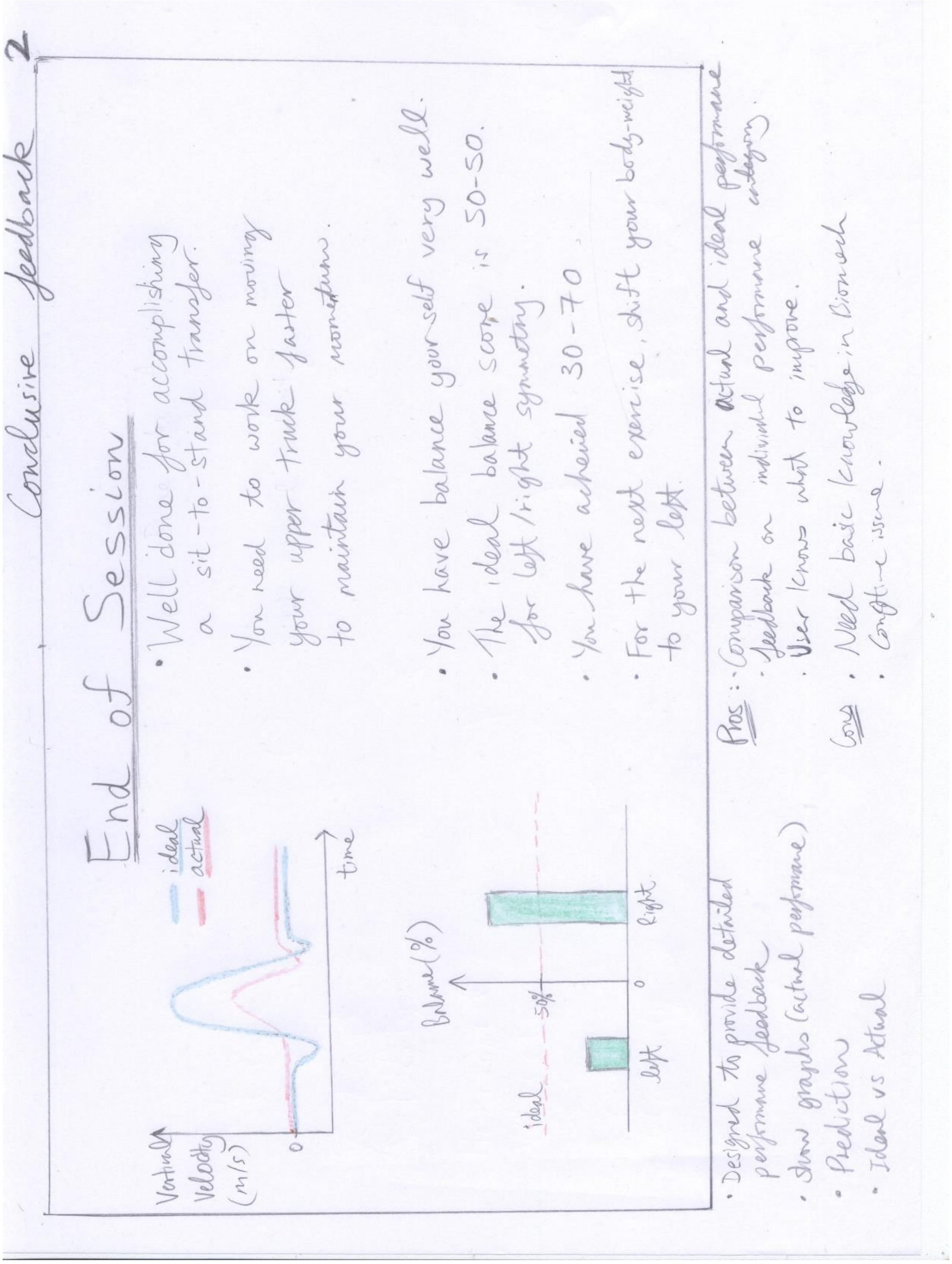
Score:

91 - 100%	A+	Prefect
81 - 90%	A	Excellent
71 - 80%	A-	
61 - 70%	B+	V. Good.
51 - 60%	B	
41 - 50%	B-	
31 - 40%	C+	Good.
21 - 30%	C	
11 - 20%	C-	
0% - 10%	D	NOT BAD.

The second concept provided more mathematical graphs and textual feedback (see figure 14):

- Emphasised on force-symmetry, upper trunk movements and vertical velocity, which are the keys to successful STS executions (see section 2.4),
- Bar charts showed average weight-loading of each side of the body,
- More textual feedback on performance. The purpose of this extra information is to help users understand their performance without additional explanation by a therapist.

Figure 14: The second conclusive feedback concept provided more mathematical graphs and textual feedback.

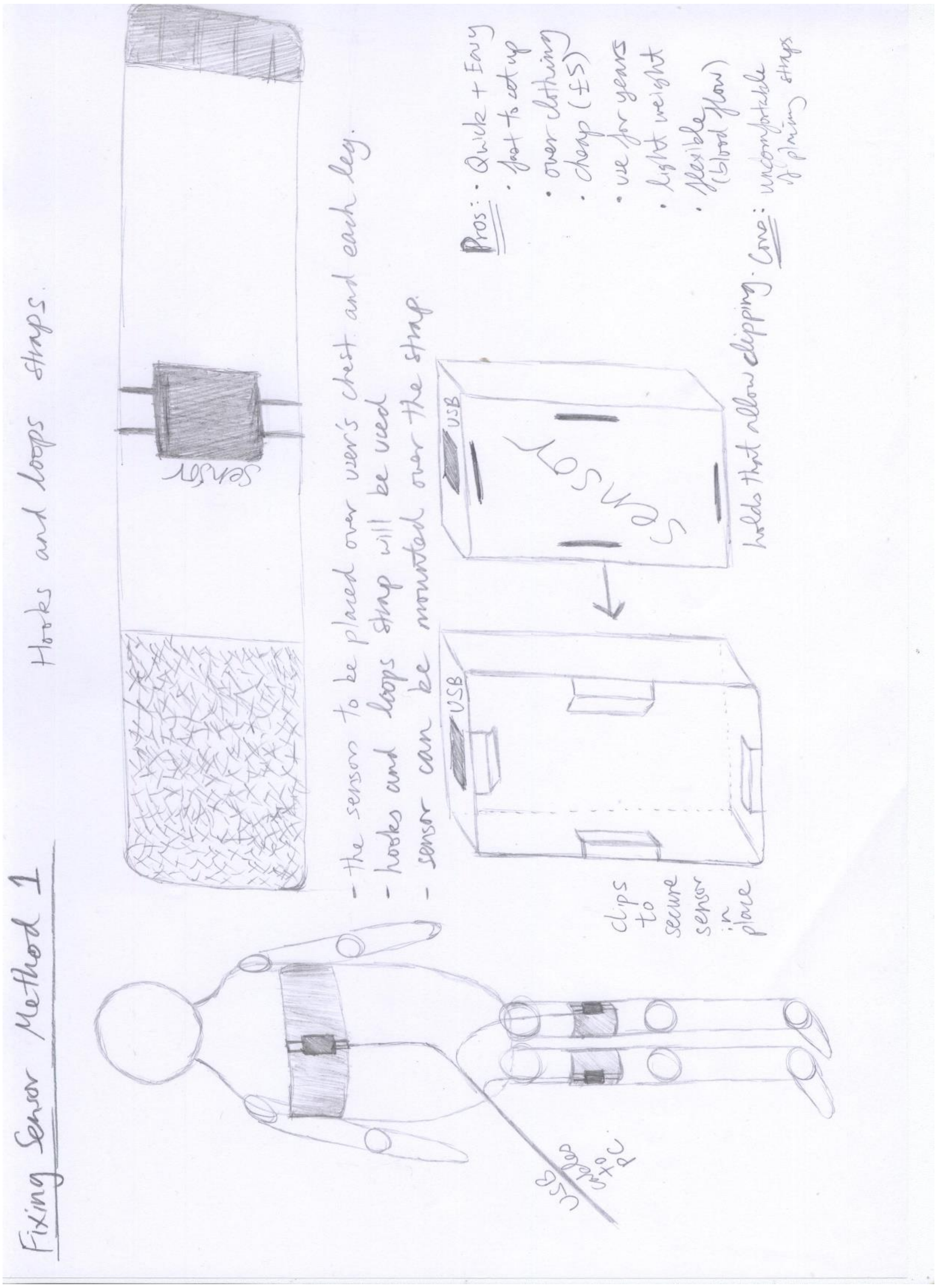


C) Portable Wearable Technology

The first concept presented the use of straps holding three wired wearable sensors for measuring real-time biomechanical performance (see figure 15):

- The first strap is mounted across the chest for measuring upper-trunk kinematics,
- The other two straps are placed on each thigh for measuring leg movements for controlling visual feedback and lower-trunk kinematics,
- Straps are made of hooks and loops. They are very low cost. They can be easily-attached, and their size can be varied quickly,
- Flexible material is used, reducing the risk of blocking blood flow.

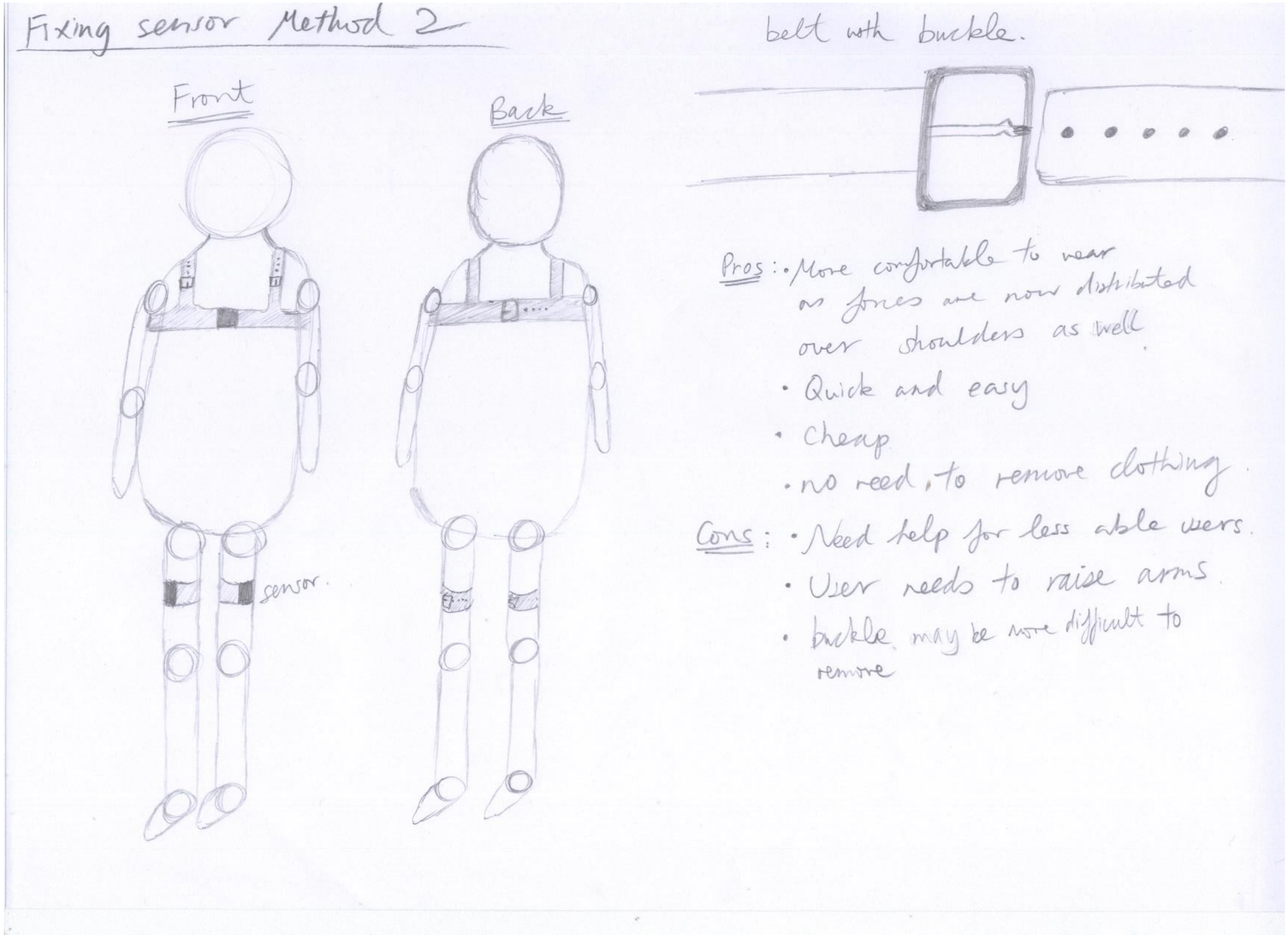
Figure 15: The first portable wearable technology concept presented the use of straps holding three wired wearable sensors.



The second concept made use of leather belts (see figure 16):

- Shoulder belts are used to reduce the chance the belts slip while in use,
- Buckles could hold the sensor in place better than hooks and loops.

Figure 16: The second portable wearable technology concept made use of leather belts.



Pros: • More comfortable to wear as forces are now distributed over shoulders as well.
- Quick and easy
- Cheap
- no need, to remove clothing

Cons: • Need help for less able wers.
- User needs to raise arms
- buckle may be more difficult to remove

3.2.3.1 Stage 3: Concept Evaluation and Selection - Methods

Two semi-structured qualitative focus-group interviews were conducted to gain feedback on and develop the concepts generated through the previous two stages. The first focus group consisted of four geriatric patients with a history of stroke and a care worker recruited from the same rehabilitation centre. These patients had not been involved in the study until this stage. They all participated in STS training and regained the independence of this movement within six months of their stroke. They were still actively involved in rehabilitation.

A second group contained two physiotherapists and an occupational therapist, who had all experienced the use of rehabilitation technology, recruited through a professional therapists' group from Lanarkshire, Scotland.

Two contrasting concepts were presented for user critique. Opinions on preferences and concerns were sought to prompt debates and determine generic responses. The first interview was recorded in audio. No audio was recorded for the second interview due to a technical fault. A thematic qualitative analysis was carried out to analyse the content obtained from the focus group interviews. All participants' demographic information was recorded.

3.2.3.2 Stage 3: Concept Evaluation and Selection – Intermediate Results

These concepts were presented to the stakeholder groups (methods described as above, section 3.2.2.1). Thematic approach analysis (Fereday & Muir-Cochrane, 2006) was used in analysing the data gathered in the focus group meetings. Four themes were identified by the researcher across all the focus groups.

Theme 1: Automation Technology

The patients and care worker shared the frustration of receiving inadequate rehabilitation care as “patients only received a couple of 20 minute sessions of rehab” with no support afterwards. The idea of providing automated feedback on performance and suggestions for improvement without the presence of a therapist was positively received by all. The concept of capturing user’s real-time biomechanical motion data for analysis using low-cost, light-weight and portable electronic sensors (e.g. inertial sensors) surprised the patients. This was also supported by therapists who wanted to avoid the inconvenience of entering data manually to obtain computerised therapeutic information. All focus group participants agreed that receiving feedback during and after practising was essential. The care worker suggested the importance of a training system shall be cheat-proof.

Examples of Response:

Participant A: **“That (concept of providing automated feedback) is a really good idea.”**

Participant B: **“It (the feedback system) acts like a physio.”**

Participant C: **“That’s (the feedback system) what we all needing now, isn’t it?”**

Theme 2: Interactions with User-Interface

Participants supported the concept of practising in a VR environment, especially one representing a bus, which the patients originally suggested was a particularly challenging situation.

Participant B: **“When I get off the bus, I have to wait until it stopped. There is no question about it. I have no real sense of balance. It would be great if I could practice the movement on the ‘bus’.”**

Physiotherapists commended the idea of generating a performance score is good if the calculations were justified. Patients disapproved of the idea of providing grades which could cause negative impacts on self-confidence if poor grades were obtained. The provision of emojis in providing feedback, including facial expressions, hand expressions and simple words, was supported but the use of negative expressions (i.e. sad face and thumb down) was discouraged.

Participant A: **“The idea of using a score is good, give you something to work on. I would go for that one (performance score), but not the grades and the faces.”**

Participant B: **“…but I am not happy with the A, B, C grades.”**

The concept of presenting scores on individual performance factor via graphical tools (i.e. coloured bar charts) was welcomed by the patients as it was easier to recognise than having biomechanical graphs, which requires prior knowledge to understand and reading of texts. Participants suggested that the system should display one type of metric at once as it could be difficult to maintain attention and control several metrics in one moment.

Participant B: **“Great to see colour indications with charts than texts.”**

Participant D: **“Simpler the better. I am sure everyone will say that. We can’t understand these graphs (biomechanical graphs) straight away.”**

Physiotherapist A: **“Texts are not useful for giving feedback.”**

Theme 3: Comfortability

Participants were pleased that the new concept required no harness and replaced by flexible straps. A patient revealed the uncomfortableness of using a harness and complained about pressure and pain in the chest and underarm regions after using a treadmill. The patients agreed that flexible straps, which they were familiar, could be operated with a single hand. However, a female patient criticised that the strap shall not be placed over the chest. Participants preferred the idea of placing the strap in diagonal on the waist. The physiotherapists suggested that the wearable electronic sensors can be incorporated to the straps, so the user will be close to normal routines as it is less notable.

Participant D: **“So it is definitely not to be placed straight across the chest.”**

3.3 Discussion

Engaging the stakeholders throughout the design process of a rehabilitation system is crucial to remove key barriers to the adoption of technologies into clinical and home environment. Previous research has indicated that a user centred approach to design is vital and should be assimilated at the earliest stage (Lu et al., 2011) (Martin, Clark, Morgan, Crowe, & Murphy, 2012) (Schnall et al., 2016). This study, to our knowledge, is the first to investigate the design features of an STS feedback system from the perspectives of end-users. Stakeholders universally acknowledged the needs for new technologies and gave support to such a system being used to deliver intensive practice of the STS movement. This is especially important since the inability to stand up from a chair is an obstacle to independence and increases the risks of injury due to falling (Cheng et al., 1998).

Design Features Emerged from the Process

Safety, ease-of-use and clinical evidence were identified as the top factors for the adoption of technologies in rehabilitation in previous studies according to end-users (A.-M. Hughes et al., 2014) (Kerr et al., 2018). Our findings corroborated this in designing an STS trainer. Our observation results revealed that over two-thirds of a therapy session were disbursed for wearing and removing a harness. The feeling of discomfort and fear of safety were also reported by some users. This inefficient tool, advised by users, should be replaced by other easy-to-use and quick-to-setup equipment (i.e. straps). Our study also expands on other critical aspects of developing the proposed system: 1) automation technology, 2) interactions with user-interface and 3) comfortability.

Research has suggested that the provision of feedback on performance enhances motor relearning experience, self-esteem, motivational value and rate of recovery (Timmermans et al., 2009). This comprises the adoption of automation technology and wearable sensors proposed in this study for the delivery of real-time and conclusive feedback (Liebermann et al., 2006) , including the use of VR, which allows person-tailored and consistent training to be achieved in simulated “real-world” scenarios. Patients are more motivated, spend more time in training and more effort into promoting recovery in a VR environment compared to traditional repetitive exercises (Broeren, Rydmark, & Sunnerhagen, 2004) (Cardoso et al., 2006) (Koritnik, Koenig, Bajd, Riener, & Munih, 2010) (Avola, Spezialetti, & Placidi, 2013).

A transport scene was identified by the geriatric patients as the most suitable “environment” for practising the STS movement due to the fact that concerns often raised by bus users when boarding and leaving the transport after they were mobility-impaired (Barnsley, McCluskey, & Middleton, 2012). Although there is research in rehabilitation video game that provides less-than-positive feedback (i.e. sad and agony iconographic) to users (Guimaraes, Ribeiro, & Rosado, 2013), this point was strongly rejected by the participants in the focus-group interviews as it could cause discouragement and knock on self-confidence.

The Strength of this Process

End-users involvement has shaped the design of a proposed STS feedback training system, thereby improving the chance of clinical and individual adoption and ultimately impacting self-management and recovery outcomes. They have elaborated at the earliest stage of the development and continuously involved throughout the design process which was invaluable in determining the current methodology and needs in STS training from different organisations and parts of the country. When determining design scopes and requirements, clinical observations of patients, therapists and care workers interactions were discovered to be beneficial compared to questionnaires or focus-group interviews as personal experience and knowledge may be challenging to articulate and participants' responses may not reflect the actual comportments. At the concept evaluation stage, participants were asked to comment on their experiences and opinions of rehabilitation but not a fully developed STS trainer. This would allow them to express freely about the preferences and design recommendations without concern about criticising the researchers' work. This chapter presents a user centred design process with a single iteration which was vital for the success of the new STS feedback training system. However, further involvement with stakeholders in assessing and evaluation of prototypes is explained in later chapters.

Limitations

The findings are limited by the demographics of the participants. None of the patients had significant cognitive issues due to the requirements of giving self-consent, able to answer the questions and analyse the generated engineering concepts. Furthermore, the patients are all elderly and opinions from younger populations were not captured. The small sample size may cause another drawback, but the findings should be viewed as exploratory research. All participants were self-directed volunteers who have a strong motivation to consider alternate technology in rehabilitation. This may have biased the study results. Overall, participants were positive about their involvement in the design process. They felt the system leveraged their insights while the ideas and solutions were mostly generated by the researchers.

3.4 Summary

Technology may offer solutions to improve rehabilitation outcome. However, their adoption rate is low. One of the reasons is because users are not often engaged in the design process. Therefore, before the technical development of the proposed STS feedback training system was started, a user centred design process was adopted in generating engineering concepts with the stakeholders for their evaluations.

Firstly, user requirements and design specifications of the proposed system were acquired through clinical observations, questionnaires and interviews. After that, multiple engineering concepts were generated using different design engineering tools (i.e. function-mean tree, morphological chart, force-fitting and SCAMPER). These concepts were evaluated at focus-group interviews with patients, therapists and a care worker. Thematic approach analysis was adopted in analysing the results and the most appropriate concepts of a new STS feedback training system, which were selected by the stakeholders, to be prototyped.

Chapter 4: Measuring and Distinguishing Sit-to-Stand Kinematics

4.1 Introduction

This chapter presents the process and argument for choosing the technology used for detecting real-time STS movements in physically impaired older adults. This is achieved by assessing currently available systems against the criteria laid out in previous chapters. Technical challenges faced when adopting the selected technology are discussed. The development and evaluation of a new novel sensor-fusion algorithm and an STS detection algorithm are also presented in this chapter.

4.1.1 Rationale for Motion Tracking in This Thesis

The aim of human motion tracking in this thesis is to provide real-time, digitised, 3D kinematic data for the generation of feedback during rehabilitation activities. In order to provide automated feedback, a motion tracking system, that is precise, robust and reliable, was needed to measure the STS motion during practice. The use of motion tracking in older people has been shown to improve rehabilitation outcomes and engagement between patients and therapists (Schwennesen, 2017).

The adopted motion tracking system must fulfil the user requirements identified through the user engagement process as discussed in chapter 3. These were:

- Lightweight,
- Portability,
- Easy to use,
- Fit for purpose in a clinical and home environment (see section 3.3.3).

There is a large range of technologies and proven motion tracking systems which could be implemented and many that could possibly have been adopted in monitoring real-time STS movements, but not without challenges for clinical implementation (Giggins, Persson, & Caulfield, 2013).

4.1.2 Current Motion Tracking Systems

There are various sensing technologies were developed for analysing human kinematics as shown in table 5. However, the adaptability of different tracking systems varies due to a range of limitations, such as requirement of a large space, inconsistent performance and high cost. In order to overview these technologies, it is convenient, classify them into two main categories based on their portability, which is a key user requirement. They are fixed-space systems, which require a capture area to deploy the motion sensing technology (e.g. cameras), and wearable systems, which require the sensing technology to be worn on the body.

Table 5: Categories of different motion capture technologies.

Category	**Types of technology**
Fixed-space	• Optoelectronic ○ Marker-based ○ Markerless • Acoustic/Ultrasonic • Magnetic • Microwave
Wearable	• Inertial sensor • Goniometer

4.1.2.1 Fixed-Space Motion Tracking Systems

Fixed-space systems operate, usually, in a studio or a laboratory environment. Optoelectronic motion tracking systems are the most dominant group of technologies for this application (Rahul, 2018). While many researchers have used these systems for tracking the STS movement (Anan et al., 2015) (Asker et al., 2016) (Kanai et al., 2016) (Paul, Lester, Foreman, & Dibble, 2016), there remain several challenges for using these systems in a home or routine clinical environment, such as a hospital ward or rehabilitation gym. The individual being tracked must change out of their usual clothes and wear form-fitting clothing before markers could be taped onto the skin. This is to ensure markers placed on the body represent the actual body motion and not clothing motion. If the markers become detached during a movement or there are errors in the anatomical location of the markers, the accuracy of the estimated joint positions could be compromised, requiring re-calibration and even recapture of a whole session.

For tracking the full body motion, dozens of markers must be attached to different locations on the body for example, thirty-eight markers are required for the Vicon full-body plug-in-gait model (Schwartz & Dixon, 2018). This is time-consuming and standing for a long period may be difficult for individuals with limited mobility. The placement of markers on the back and posterior pelvis poses specific problems for capturing the STS movement with the potential occlusion from the back of the chair. Marker occlusion is likely to be a major concern in a home or busy clinical environment with markers blocked by furniture and movement of staff or carers support the individual. While alternative modelling procedures could be adopted to “simulate” occluded markers, the results are likely to include additional, potentially large errors (McClelland, Webster, Grant, & Feller, 2010).

The effort needed for calibration and pre-capture set-up (Ceseracciu, Sawacha, & Cobelli, 2014), high cost (Bolink et al., 2016), extra training and the need for an skilled operator (Marin, Blanco, & Marin, 2017) restrict the use of these motion tracking systems and making translation to everyday rehabilitation setting difficult and unlikely. In fact, in the United Kingdom, there are only thirteen optoelectronic laboratories for clinical operations (Clinical Movement Analysis Society U.K. & Ireland, 2018).

Markerless systems, as the name indicates, require no markers to be placed on the body. Although they eliminate the inconvenience of wearing markers, the view of the cameras still cannot be blocked by an object, such as a therapist or a chair. Therefore, the space must be empty of all other objects, which is problematic for the STS movement.

Another type of fixed-space motion tracking technology uses acoustic operations. However, the physics of acoustic waveforms (i.e. low-frequency as slow as 10 Hz), constructive and destructive inferences, mean the rate of captures is as low as 10 Hz and with a resolution of approximately an inch (Welch & Foxlin, 2002). Its low refresh rate is unlikely to be suitable for real-time motion tracking. Moreover, the tracked subject must be in a clear sightline at all time without interference in the soundwave reflection. An object, such as a chair would, therefore, prevent the system tracking the motion accurately. Sound noise generated by movements could also interfere with the signals.

Ultrasonic trackers use high-frequency ultrasound waves (40 kHz to 80 kHz) to determine positions of the human body. They have higher refresh rate (about 40 Hz) (Fast, O’Shea, Nill, Oelfke, & Harris, 2016), nevertheless, obstacles will still pose a problem with reception. Therefore, acoustic and ultrasound technologies have not been deployed in rehabilitation environments and remain in the research and development phase. Technologies using electromagnetic waves, such as radio-waves and microwaves, have not been well exploited in motion tracking because of their poor performance to date (Welch & Foxlin, 2002).

In the next section, wearable motion tracking systems will be discussed as an alternative to fixed space systems.

4.1.2.2 Wearable Motion Tracking Systems

Wearable technologies are electronic devices that can be worn on the human body. They are usually miniaturised and lightweight. The number of individual wearable devices globally stands at 325 million in 2016 and is expected to reach 929 million by 2021 (Nace & Pióro, 2008). In the same year, a total of 33.9 million units of fitness trackers alone were shipped (Cnet, 2017). The innovation in wearable devices also provides a portable method for 3D motion tracking. They are not space confined nor require a large space for equipment accommodation. Thanks to new techniques in ubiquitous computing, compact and lightweight wearable sensors are capable of recording 3D kinematic data (linear accelerations and rotational velocities) and can be directly attached to a human body.

Wearable mechanical suits, such as the Gypsy 7 system (MetaMotion, San Francisco, CA, USA), incorporate electro-goniometers for tracking body motion. These systems aim to measure angular displacement of anatomical joints. However, they have limited use in motion tracking because of their low accuracy (over 40% of the measured angles) (Lorussi, Galatolo, & De Rossi, 2009). Moreover, the fixed frame attached to the body restricts natural movement and is particularly problematic for the STS movement as it must be fixed to the back, preventing a natural and comfortable sitting posture.

4.1.2.3 Micro-Electro-Mechanical-Systems Technology

Recent advancements in micro-electro-mechanical-systems (MEMS) have led to the use of inertial sensors for motion tracking. Originally, in the mid-twentieth century, inertial sensors were widespread in navigational systems on transport, such as aeroplanes, submarines and sea vessels, to provide precise and accurate directional information as the global positional system was not available (Ciuti, Ricotti, Menciassi, & Dario, 2015). Early sensors contained gyroscopes with large spinning rings that would be too large and too heavy to be placed on a human body (Passaro, Cuccovillo, Vaiani, De Carlo, & Campanella, 2017). New developments in microfabrication techniques have minimised the size of inertial sensors to less than several cubic centimetres and only a few grams in weight. These developments have also facilitated mass-production driving the cost down (Aktakka, Woo, & Najafi, 2017) so that an inertial sensor may only cost as little as $10 (GY-85, HALJIA, Shenzhen, China).

An inertial sensor consists of two MEMS integrated circuits, an accelerometer and a gyroscope, both measuring three-axial motions. An accelerometer measures “proper” acceleration. It does not measure external acceleration it experiences but detects acceleration due to free fall. For instance, an accelerometer at rest would provide a reading of 9.81 ms^{-2}, the Earth's standard gravitational acceleration. However, if it experiences free fall, an acceleration due to gravity, its measurement will remain 0 ms^{-2}. In other words, the acceleration data consisted of static acceleration due to the Earth’s gravity and dynamic acceleration due to movements. The gyroscope determines rotational movements and the sensor’s orientation. It acquires angular velocity due to external rotations.

These sensors can provide 3D kinematics in six independent parameters, accelerations and angular velocities each in three directions. Therefore, these systems also are known to have 6-DOF (degrees of freedom) (Y. Zhang, Sapir, Markovic, Wagenaar, & Little, 2011). The latest generation of inertial sensors also comprises a three-axial magnetometer that defines the sensor’s heading by measuring the Earth’s magnetic field (Filippeschi et al., 2017). The continuous enhancement in technical aspects of the technology as well as lowered cost (tens of pounds), weight (tens of grams) and size (several cubic centimetres), increase their usage in the consumer industry, robotic instruments and in the fields of motion tracking (Ahmad, Ghazilla, Khairi, & Kasi, 2013).

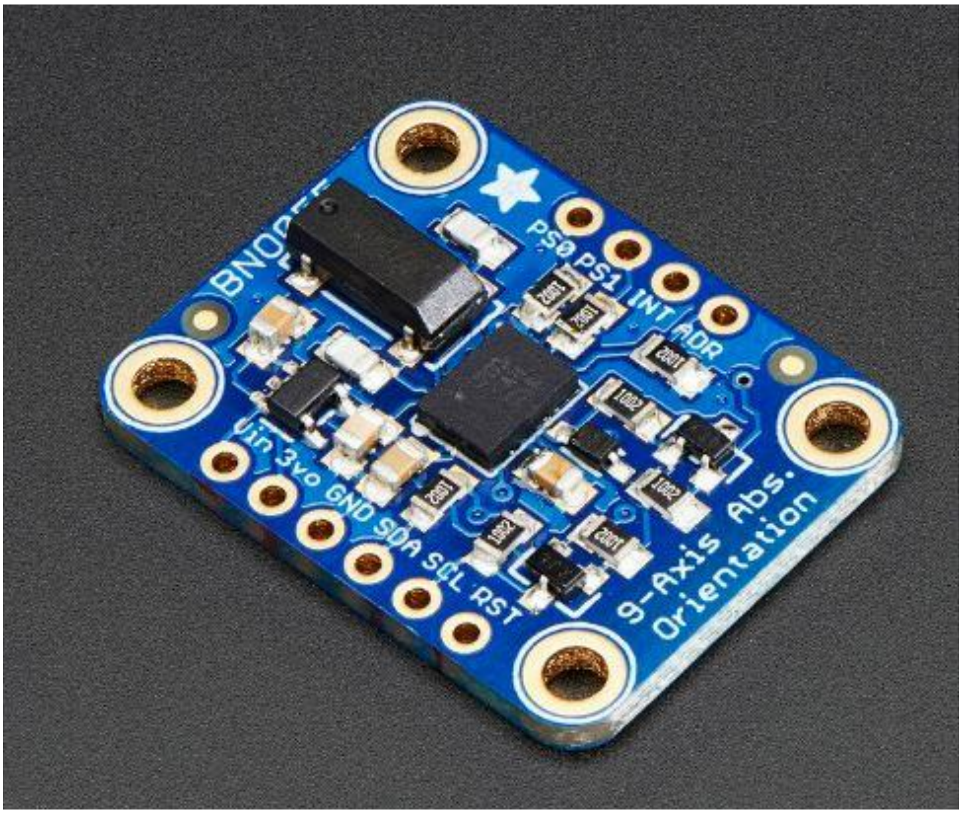


Figure 17: A wearable inertial sensor, Adafruit 9-DOF IMU L3GD20H. Size: 38mm x 23mm. Weight: 2.8g (Adafruit Industries, New York City, New York, United States).

In healthcare, inertial sensors have been used for measuring the level of daily physical activities (Najafi et al., 2003) (Hegde, Melanson, & Sazonov, 2016), characterising postures of functional tasks (Sellers, Dall, Grant, & Stansfield, 2016), fall detection (Najafi, Aminian, Loew, Blanc, & Robert, 2002) (Redmond et al., 2010) and physical performance (Lugade, Fortune, Morrow, & Kaufman, 2014).

For instance, Tunca et al. (2017) adopted inertial sensors in analysing gait movements in patients with neurological disorders. An inertial sensor was strapped to each foot. As soon as a gait movement was initiated, data about the accelerations and angular velocities were transmitted to a processing unit to work out gait metrics, such as stride length, stance ratio, foot clearance, speed and cycle time (Tunca et al., 2017). Bolink and colleagues (2012) had also experimented the use of inertial sensors for analysing the STS movement and step transfers (Bolink, Van Laarhoven, Lipperts, Heyligers, & Grimm, 2012). Both studies suggested the use of inertial sensors is accurate, reliable and feasible when capturing kinematics data on mobility impaired patients.

4.1.3 Force Sensing Technology

In order to conduct an accurate assessment of STS performance, analysis of the ground reaction force (GRF) when transitioning from a seated to a standing position, is essential (McGibbon, Goldvasser, Krebs, & Scarborough, 2004) (Mazzà et al., 2005) (Tsuji et al., 2015). Therefore, a suitable force measuring system was required.

Force sensing technologies are widely adopted in rehabilitation for assessing changes in the body's centre of pressure (CoP) and GRF in order to quantify different biomechanical parameters, such as force-loading (Mengarelli et al., 2018), gait parameters (Yiou, Teyssèdre, Artico, & Fourcade, 2016), sit-stand repetitions (Abujaber, Gillispie, Marmon, & Zeni, 2015), kinematics of jumps

(Yamamoto & Matsuzawa, 2013) and postural stability (Yiou et al., 2016). Force platforms, also known as force plates, are commonly used in rehabilitation to research falls prevention and functional training (Mazzà et al., 2005).

Based on Newton’s third law, forces are always acting in a pair, an equal but opposite interaction pair. When a person is standing, their weight, the action force, exerts a downward force on the ground. The ground also exerts the reaction force that is equal but in opposite direction to the action force. This reaction force is what is being measured by force platforms. In other words, force data are a measurement of the reaction of the plate on the ground to any weight being distributed onto it.

4.1.3.1 Types of Force Sensing Technology

Force plates are installed with force sensors which convert physical quantities (strain) into electrical signals. When a force is applied to these sensors, the material inside them is “distorted” and compressed in length. This change is proportional to the variation in electrical resistance and voltage. The resulting electrical analogue signals from the load cells are converted into discrete digital signals, through an analogue to digital converter, which then be measured and worked out the magnitude of forces applied (Beckham et al., 2014). The surface of the force plate is flat with the load cells are installed on various parts of the plate (such as one in each corner) so that the correct direction and magnitude of forces (in X, Y and Z axis) can be acquired. Mathematical calculations were used to derive other variables, such as the CoP and moments, to quantify key aspects of movements.

There are different types of force sensing technology which are used in the rehabilitation setting: fixed force plates, portable force plates and wearable force sensors.

4.1.3.2 Force Plates Comparison

Force plates can be separated into two categories: fixed force plates and portable force plates. Fixed force plates are also known as laboratory-grade plates as they are the gold standard for use in rehabilitation for their reliability (M. G. Silva, Moreira, & Rocha, 2017). They are often installed and fixed on the ground in an enclosed environment, such as a biomechanical laboratory. This is to prevent measurement inaccuracy due to an uneven floor. Also, to reduce noise from the floor vibrations, they are mounted on steel platforms and put under the ground level so that the surface is flush with the ground. Any movement of the plate may alter the accuracy of the results, however, these plates are not designed to be moved, weighing up to 32 kg (6012-15, Bertec Corporation, Columbus, OH, U.S.A).

Portable plates, on the other hand, are usually lighter. For instance, the Kistler 9260AA3 portable plate (Kistler Group, Winterthur, Switzerland) weighing only

5 kg. They can be operated wirelessly, meaning they are easier to move around. However, they have limited performance compared to fixed force plates. For example, the error from a fixed force plate (e.g. Kistler 9218B, Kistler Group, Winterthur, Switzerland) in measuring CoP sway is in the range of tens of micrometres compared to a portable force plate, the Wii balance board (Nintendo Co. Ltd, Kyoto, Japan), in the range several millimetres (Huurnink, Fransz, Kingma, & van Dieën, 2013).

The price of portable plates (such as $80 for a Wii balance board shown in figure 18) is competitive for use in rehabilitation. However, this restricts manufacturers from installing high-quality sensors into these systems. They often have more mechanical and electronic limitations than fixed plates and usually rather expensive (usually around several thousands of pounds). Jittering due to inconsistent sampling rate across the four sensors (Audiffren & Contal, 2016), low sampling rate at tens of Hertz and resolution of only 0.5 mm (Leach, Mancini, Peterka, Hayes, & Horak, 2014) are all sources of uncertainty in the data collected from portables plates.

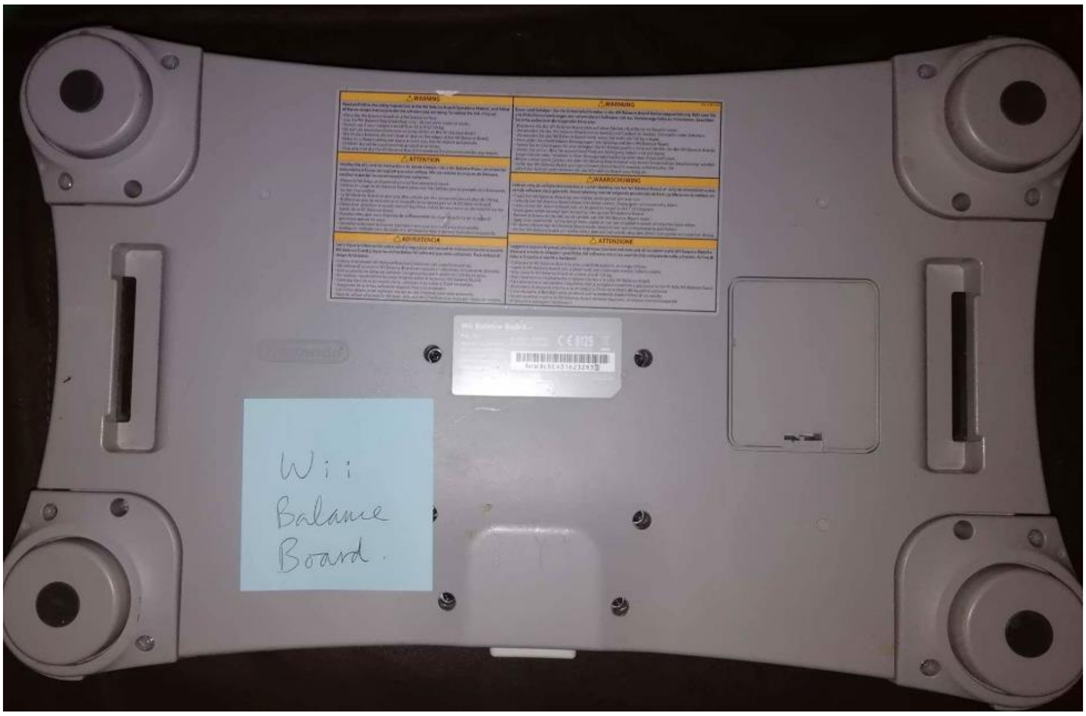


Figure 18: A portable force plate (Wii balance board) consisted of a strain gauge transducer in each of the cylindrical leg.

Moreover, fixed plates are composed of metal or glass, while many portable plates such as the Wii balance board, are made of plastic. Because of the material properties of plastic, their mechanical supports, which touch the ground in measuring the GRF, and the usable surface are susceptible to elastic deformation. When a load is applied to the plate, the obtained measurements will be affected by the deformation of the plate leading to less accurate data compared to fixed plates.

The force sensors in fixed plates are arranged to detect orthogonal forces and allow measurements in three-axes. Portable plates typically consist of uniaxial sensors. Being unable to separate and record the shear components of a movement means the signals may include errors (Leach et al., 2014).

New portable force plates such as the Pasco PS-2142 (Perform Better Limited, Southam, Warwickshire, U.K.) and Bertec 50 (Bertec Corporation, Columbus, OH, U.S.A.) have emerged on the market. These mid-price range plates (£420 for a NEULOG Force Plate, Drexel Hill, PA, U.S.A) provide affordable force measurements with good performance in rehabilitation: sample rate at hundreds of Hertz, consistent sampling rate, three axial measurements and load capacity of tens of kilonewtons (compared to several kilonewtons in low-range portable plates) (Robinovitch & Sandler, 2001) (Pline, Madigan, & Nussbaum, 2006) (Peterson Silveira et al., 2017).

4.1.3.3 Wearable Force Sensors

Wearable force sensors are embedded under the feet, on top of an insole to measure the force applied by the plantar soft tissue under the feet on the shoes, hence the force applied to the ground. They are able to provide quantitative and repeatable results making them widely adopted in clinical gait analysis (Morris & Paradiso, 2002) (T. Liu, Inoue, & Shibata, 2010), measuring muscle strength (Abdul Razak, Zayegh, Begg, & Wahab, 2012), postural analysis (Sazonov, Fulk, Hill, Schutz, & Browning, 2011) as well as STS quantification (Doulah, Shen, & Sazonov, 2016).

Capacitive (Salpavaara, Verho, & Lekkala, 2008) and piezoresistive (Robinovitch & Sandler, 2001) sensing are among the most popular methods used for this application. Both types of sensors are made of flexible materials including their circuit boards. When a force is applied, the fabric is compressed, and its electrical characteristics vary accordingly. For capacitive sensors, the change in capacitance when the fabrics are being compressed or stretched is sensed by a capacitance to digital converter on the circuit boards then processed by more electronics and signal processing algorithms in order to interpret the actual force applied to it (Salpavaara et al., 2008). The idea of piezoresistive sensing is very similar but electrical resistance is being varied and measured instead of capacitance (Robinovitch & Sandler, 2001).

Wearable force sensors could be used when measurements made in everyday situations are not feasible with force plate technology. For example, analysing gait movements on an uneven surface in an outdoor environment (Abdul Razak et al., 2012), walking an undefined path in a non-constrain direction (Hausdorff, Cudkowicz, Firtion, Wei, & Goldberger, 1998) or patients who have no ability to make contact with force plates. Moreover, sensor slipping is an issue when monitoring movements (MacWilliams & Armstrong, 2000). They do not, typically, provide shear.

4.1.4 Suitability for Use in STS Training

Given the criteria laid out in chapter 3, a suitable motion tracking and force sensing technology were chosen for use in training the STS movement. This technology must fit the user requirements, easy-to-use, miniature (its length, weight and height must all within several centimetres if to be worn), affordable while providing high measurement accuracy (within a range of several millimetres) were the key factors. The system must be fit for use in a clinical environment, such as hospital wards, preferably, at homes too, given the device is user-friendly and quick to set-up (see table 6).

For motion tracking technologies such as optical and acoustic systems, that would require a clear line of sight and cannot be blocked by any objects, like a chair or standing aids, were unsuitable for use. This is because therapists could be blocking the sightline in front or beside the tracked subject when giving support for safety. Wearable inertial sensors provided the best solution for this purpose.

In terms of force sensing, a laboratory-grade force plate could provide highly accurate measurements. But they are not feasible in the clinical environment, such as a hospital ward, as patients must be transported to a separate location to use a fixed force plate. The issues with slippage and the time required to install and remove wearable sensors from shoes are not time sufficient in the clinical environment. A mid-range portable force plate is the best solution and met the user requirements of portable, affordable (hundreds of pounds) and provide high measurement accuracy (within a range of several millimetres) for providing biofeedback.

Table 6: The choice of equipment meeting the requirements that used for the search of appropriate technology.

Requirements	**Choice of equipment meeting the specific requirement**	
	Inertial Sensor	Balance Plate
Easy-to-use	✓	✓
Quick-to-set-up	✓	✓
Portable	✓	✓
No need a clear line of sight	✓	✓
Miniature (its length, weight and height must all within several centimetres if to be worn)	✓	N/A
High accuracy (within a range of several millimetres)	✓	✓
Affordable (hundreds of pounds)	✓	✓

4.1.5 Challenges to Using Inertial Sensors to Measure Linear Quantities

Raw output data from inertial sensors, particularly low-priced devices which have inherently lower precision and reliability, are erroneous and contain non-ideal characteristics (Ahmad et al., 2013) (Wei et al., 2013) due to the cheaper materials built-in to the sensors. For instance, ADIS16003 accelerometer (Analog Devices Inc, Norwood, Massachusetts, U.S.A) costs $18.50 has non-linearity of ±2.5% of full scale and ADXL1005 accelerometer from the same manufacturer costs $39, only has non-linearity of ±0.25% of full scale. These characteristics create several technical challenges to ensure the resulting data are good enough for believable and accurate real-time and conclusive feedback.

4.1.5.1 Integration Errors

Integration drifts occur when obtaining velocity and displacement. To obtain velocity from acceleration signals, firstly, dynamic acceleration must be extracted from the measured “proper” acceleration by eliminating static acceleration purely due to the pull of gravity. After that, time-integration must be achieved. However, as noises, such as white noise, 50 Hz noise and other non-ideal characteristics, like non-linear responses, resolution errors, jittering sampling rate and offset are present in the signals. These errors are also being integrated into velocity which brings an accumulation of errors to the calculated velocity. Moreover, when integrating, low-frequency components of the signals are amplified, and the high-frequency components are reduced. This causes phase shifts (Arraigada & Partl, 2006). All these errors will accumulate over time. Their reduction is critical to improve the quality of the feedback data.

When estimating displacement, acceleration signals must be double time-integrated, and this process integrates the errors twice. Even a small error (0.01%) in the acceleration signals, the estimated displacement could be overestimated by ten times its original value within several seconds as shown in figure 19 (Thong, Woolfson, Crowe, Hayes-Gill, & Jones, 2004). The errors dominated the estimated results. Therefore, direct time-integration on acceleration signals to obtain velocity and displacement is not feasible as it will cause unrealistic drifts in the estimations. This problem also affects angular displacement when calculated from angular velocity obtained from the gyroscope (Bergamini et al., 2014). Moreover, the initial conditions of the time-integration process are unknown, and this would affect the calculated results.

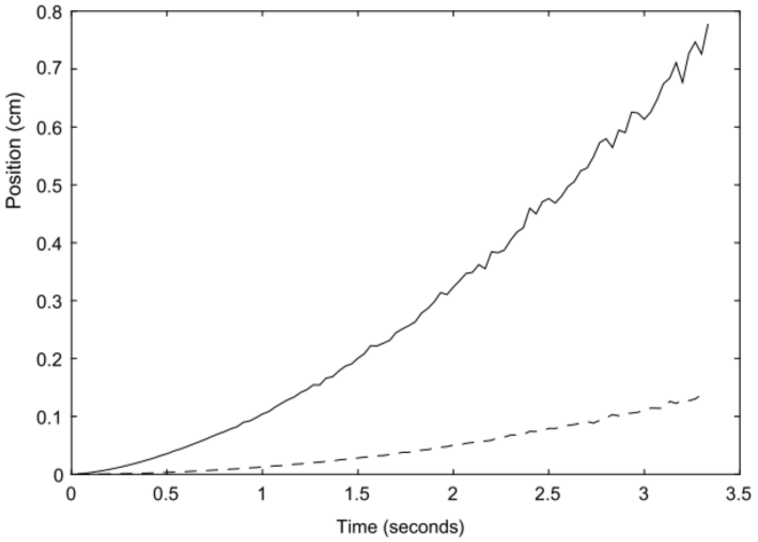


Figure 19: *The dotted line shows the actual position of an inertial sensor. The whole line shows the estimated position due to integration errors. After a few seconds of estimation, the errors increase exponentially (Thong, Woolfson, Crowe, Hayes-Gill, & Jones, 2004).*

4.1.5.2 Challenges of Using Inertial Sensors for Angular Displacement

A MEMS accelerometer measures both static and dynamic accelerations. The outputted acceleration signals are a vector sum of both accelerations. Static acceleration measures gravitational acceleration while dynamic acceleration is the actual external acceleration experienced by the inertial sensor. By obtaining the precise orientation of the inertial sensor (i.e. the angle of tilt of the sensor) in real-time, the gravity component can be removed, thereby reducing inaccuracies, in the resulting raw acceleration signals (Y. Zhang et al., 2011). Moreover, knowing the real-time orientation of the inertial sensor, is important to adjust the coordinate system of the obtained data from the sensor reference frame (i.e. inertial sensor) to global reference frame (i.e. with respect to the Earth) that studies have used in analysing human motions, including the STS movement (Bleser & Stricker, 2009).

This real-time orientation information could be extracted from the gyroscope. Gyroscope detects the rate of change of angular orientation in 3D and it does not susceptible to external forces. Rotational angles could be obtained by time-integrating that signals. Nevertheless, the temperature of gyroscopes rises during operation and the stiffness of electrical materials inside the chip will change with the increasing temperature. This affects its electrical characteristics and produces an offset in the output signals (Xia, Chen, Wang, & Li, 2009) (see figure 21).

These properties prevent accurate estimations of inclination information from time-integrating angular velocity as this process would lead to further drifting as shown in figure 22. It is possible to determine degrees of tilt by only using acceleration signals as trigonometry could be used to solve for the resultant vector of the force of gravity in the three-axial accelerations measured (Stančin & Tomažič, 2011), given the accelerometer is stationary. The reason for that is, this process does not involve time-integration and the issue of drifting could be eliminated. Nonetheless, any sudden movements due to external accelerations, the estimations would become erroneous and not be able to distinguish the difference between dynamic acceleration due to any motion and static acceleration due to the Earth’s gravity. This phenomenon does not affect gyroscopes as gravity has no impact on its measurement, unless the system was experiencing high acceleration (>10 ms^{-2}) (Bancroft & Lachapelle, 2012).

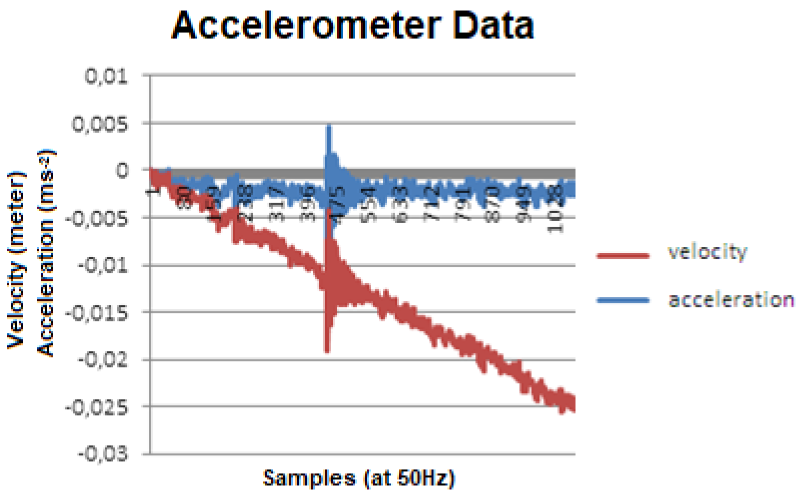


Figure 20: Integration drifts affecting the estimation of linear velocity (as shown in red).

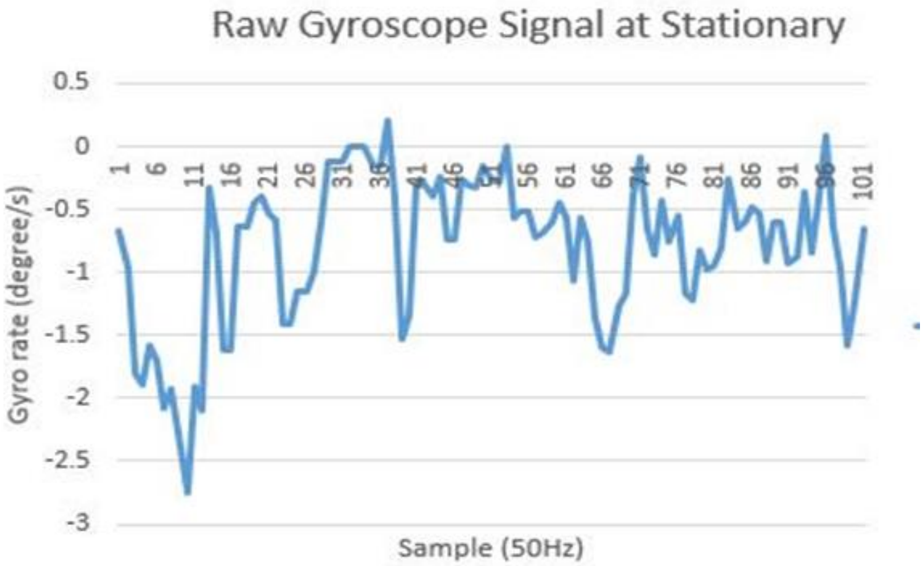


Figure 21: Angular rate measured by a gyroscope when it is stationary.

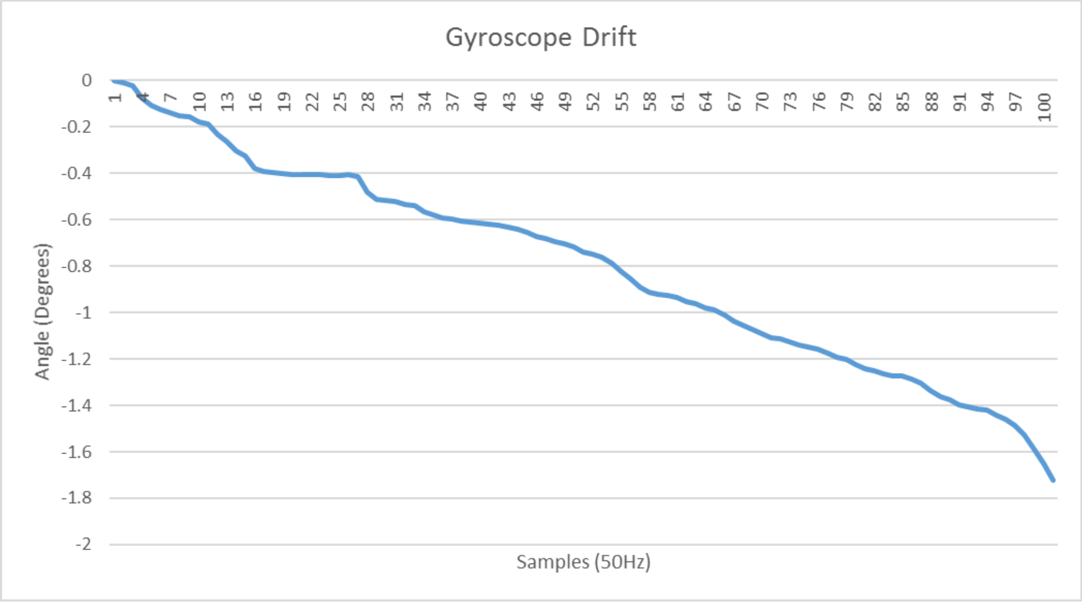


Figure 22: Integration drifts occur when estimating angular displacement by time-integrating raw gyroscope signals.

Table 7: Pros and cons of accelerometer and gyroscope in estimating angles and linear quantities.

	Angle Estimation	**Velocity/Displacement Estimation**
Accelerometer	• No drifts • Affected by linear acceleration/gravity	• Impossible to correct zone sensitivity issues on its own • Integration drifts due to the accumulation of errors when time-integrating acceleration
Gyroscope	• Suffers from temperature drifts • Not affected by linear acceleration/gravity	• Able to provide inclinations to fix zone sensitivity issues • Remove sensitivity errors and (some) integration drifts

4.1.6 Sensor-Fusion Algorithms for Detecting Kinematics

Neither a stand-alone gyroscope nor accelerometer alone can provide a precise orientation estimation for a body segment. Implementing a suitable sensor-fusion algorithm which combines the signals gathered from both sensors can compensate for their relative weaknesses and at the same time derive a solution for correct estimates. The section discusses the main sensor-fusion techniques used in research for the application of measuring human motions with inertial sensors.

4.1.6.1 Complementary Filters

The frequency spectra of signals from accelerometers are lower than gyroscopes. In order words, the slow-moving acceleration signals are fused with rapidly changing signals from gyroscopes when estimating orientations. In a complementary filter, the accelerometer signals would first pass through a low-pass filter as shown in figure 23. This removes rapidly changing external forces. Hence, the low-pass filter is treating dynamic accelerations as noise which is causing some disturbance in the measurements and keeping the static accelerations. The gyroscopic signals applied with a high-pass filter to remove offset due to rising temperature. The combined frequency response of both filters must equal to one at all frequencies. Therefore, the orientational information at any point of time is not subjecting to either low or high pass.

$$\theta_{k+1} = (1 - G)\left(\theta_k + \int \omega \, dt\right) + G \times a$$

$$where\ the\ transfer\ function, G = \frac{\tau}{\tau + dt}\ and\ dt = \frac{1}{f_s}$$

The major advantage of this type of technique is its efficiency, requiring minimum computing resources for estimating angles when compared to other sensor-fusion methods (such as the Kalman filter and particle filter) (Islam, Islam, Shajid-Ul-Mahmud, & Hossam-E-Haider, 2017). Its ability to remove non-ideal characteristics of both signals, however, is limited. This simple algorithm ignores the noise present in the process. Overestimation (up to 50%) (Cao, Qu, Li, & He, 2009), inability to filter various sources of noise with its complementary spectral characteristics (Bachmann et al., 1999), statistical inconsistency and error divergence (Lustosa, Pizziol, Defaÿ, & Moschetta, 2016) have all been reported when using this method for estimating angles.

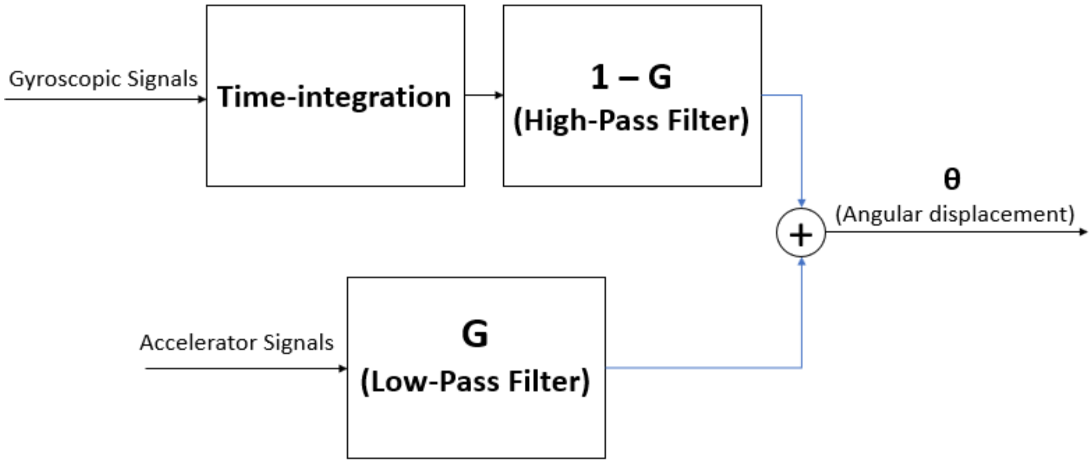


Figure 23: Complementary filter overall architecture.

4.1.6.2 Sequential Monte Carol Methods

The Sequential Monte Carol (SMC) method was first introduced by Hammersley and Morton in the 1950s for nuclear physics applications (Hammersley & Morton, 1954), also known as particle filters. It was a set of simulation-based methods used in estimating unknown quantities from some given observations (Del Moral, Doucet, & Jasra, 2012). In the case of dealing with signals from an inertial sensor, this method first observes the prior distributions, a set of “particles”, for the noise and erroneous measurements in the accelerometer and gyroscopic signals (see figure 24). After this stochastic process, it formulates an appropriate probability density model that predicts the process and measurement noise and its likelihood functions relating to the raw signals.

This method implements the prediction-updating transitions. As more data becomes available, it learns and updates the prediction model from time-to-time for more accurate noise estimation (Del, Université, & Sabatier, 1998).

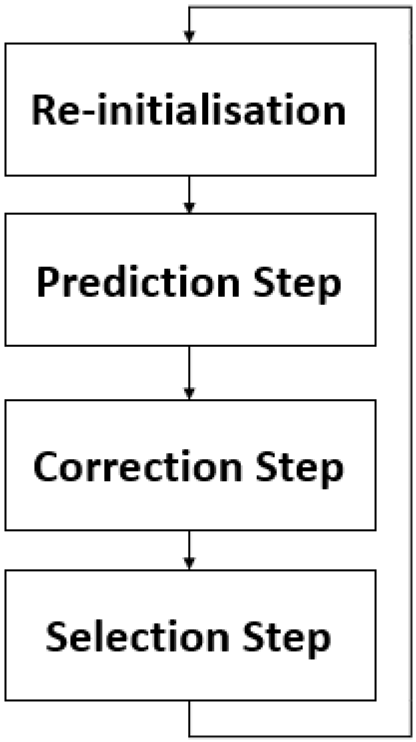


Figure 24: Flowchart showing each step of the Sequential Monte Carol Method.

However, because the model generates estimations without requiring assumptions about a state-space model. Its performance is limited when applied to systems which consisted of several dimensions with more state variables, such as approximating three-axial angles and three-axial accelerations at the same time. For this model to perform well, it also requires a large number of particles. The computational resources needed increase exponentially with the number of state variables and may take more computational resources than may be available (Bolić, Djuric, & Hong, 2004). If this is a problem, “particle depletion” would occur and the correct estimate may disappear permanently unless resampling of a very large number of particles occurs once again (Jing, ChongZhao, & Vadakkepat, 2010).

For instance, Melo and Matos found the method was “useless” when tracking headings and directions (Melo & Matos, 2013). The process noise generated was reported to have changed the behaviour of the predictions and dominated the noise from the input data (Ruth, 2002). In fact, due to issues with this method, it is frequently used with another data source to enhance its performance when implemented to deal with signals from inertial sensors, such as combining with a GPS to measure distance (Ruth, 2002) (Abd Rabbou & El-Rabbany, 2015) and using Wi-fi signals to estimate positions (Atia, Korenberg, & Noureldin, 2012).

4.1.6.3 Kalman Filtering

Also known as linear quadratic estimation, Kalman filtering requires much lower computational resources (Islam et al., 2017). This approach was introduced in the 1960’s by Rudolf E. Kálmán (Kalman, 1960). It was well known for its adoption in NASA’s Apollo program, landing the first astronauts on the Moon, just as importantly, bringing them back to the Earth, for solving space navigation issues in trajectory estimation and control problems (Grewal & Andrews, 2010).

Kalman filter is based on a linear state-space model that observes the inputs, which contain inaccuracies and noise, over a period of time. Very similar to the SMC method, Kalman filter “learns” from the input data and estimates the unknown variables. In the case of detecting kinematics using inertial sensors, the unknown variables are noise, non-ideal errors and drifts. However, in contrast, it only stores a previous set of input samples when estimating these quantities, making it much more memory efficient compared to the SMC method. In fact, Kalman filter is currently the most commonly used sensor-fusion algorithm and considered to be the optimal method for real-time application with continuously changing signals (Faragher, 2012).

What makes Kalman filter unique is that it consists of two distinct processes, prediction process and correction process. Both processes are executed in a recursive manner, one following the other, to achieve Kalman filtering as shown in figure 25. The processes correlate both the actual measurement errors and prediction errors and combined them in the overall filtering process in order to estimate the best true values of the interested variables (Gamse, Nobakht-Ersi, & Sharifi, 2014).

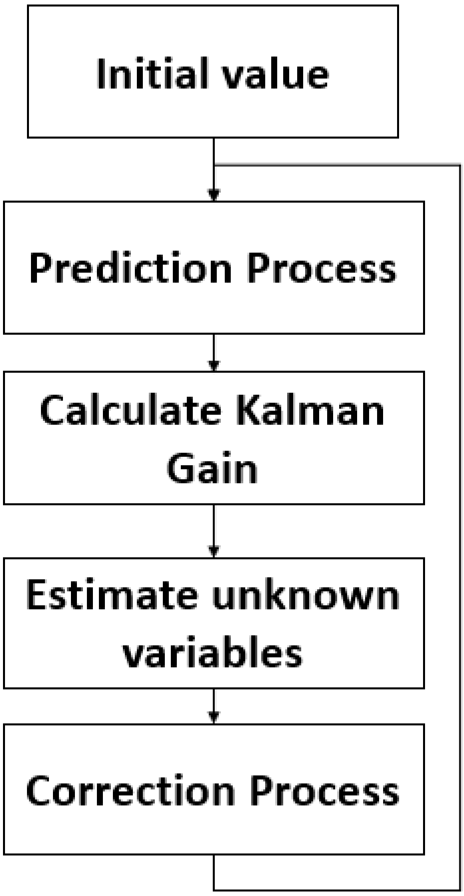


Figure 25: Flowchart showing each step of Kalman filtering.

The Kalman filter has been adopted in many studies of human kinematics: gait analysis (Boyd, Santos Costa, Davis, & Page, 2012), head tracking (Asghari Oskoei, 2017), upper-limb movements (Bagherpour, Cheraghi, & Bin Mohd Mokji, 2012) (Tian, Meng, Tao, Liu, & Feng, 2015), postural control (Olivares, Górriz, Ramírez, & Olivares, 2016), sporting activities (Zihajehzadeh, Loh, Lee, Hoskinson, & Park, 2015) and energy expenditure (Williams, Li, & Pathirana, 2018) have all used a Kalman filter.

4.1.7 Sensor-Fusion for Real-Time STS Movements

The use of a sensor-fusion algorithm is essential to tackle the non-ideal characteristics of signals acquired from an inertial sensor. As indicated in the previous sections, both the complementary filter and the SMC method posed a limitation on estimating accurate and precise kinematic information. However, the Kalman filter, which is widely adopted in human motion studies, is an ideal solution to these challenges and its high computational efficiency means a low-cost computer can be used.

The use of a Kalman filter can reduce errors when capturing kinematics of human motion, including the STS movement, but most developed algorithms are designed for and tested by healthy individuals (Mathie et al., 2004) (Godfrey, Barry, Mathers, & Rochester, 2014) (Salah et al., 2014). Research has also shown that the processed kinematic data can be analysed by adaptive algorithms for defining events, timing and duration of the STS movement for performance examination in healthy individuals (Costantini, Carota, Maccioni, & Giansanti, 2007) (Arcelus et al., 2009) (Doulah et al., 2016). A suitable algorithm is needed for detecting the STS movement in impaired populations such as geriatric patients whose STS performance and characteristics are different when compared to healthy individuals, as discussed in section 2.4.

Therefore, the aim of this part of the project was to develop a specific Kalman-filter algorithm to minimise errors when measuring STS kinematics in geriatric patients using an inertial sensor and a portable force plate. In addition, an adaptive algorithm for detecting STS events in geriatric patients was developed for providing the required movement feedback, both in real-time and following movement practice.

4.2 Methods

This section describes the design of a new bespoke Kalman filter based sensor-fusion algorithm to estimate real-time linear velocity and angles of the motion of the human body trunk when standing up from a sitting position (see figure 26). This algorithm accepts three-axial acceleration signals fetched from an accelerometer, three-axial angular rotations from a gyroscope and force data gathered from a force plate.

The robustness of the system was tested with a concurrent validity study where the data collected from the system was compared, concurrently, with a gold standard motion capture system (Vicon motion capture, Oxford, U.K.), in a motion capture laboratory using mobility-impaired older adults (previous stroke), n = 5. This study was given institutional ethics board approval (University of Strathclyde, University Ethics Committee, Reference Number: UEC16/02).

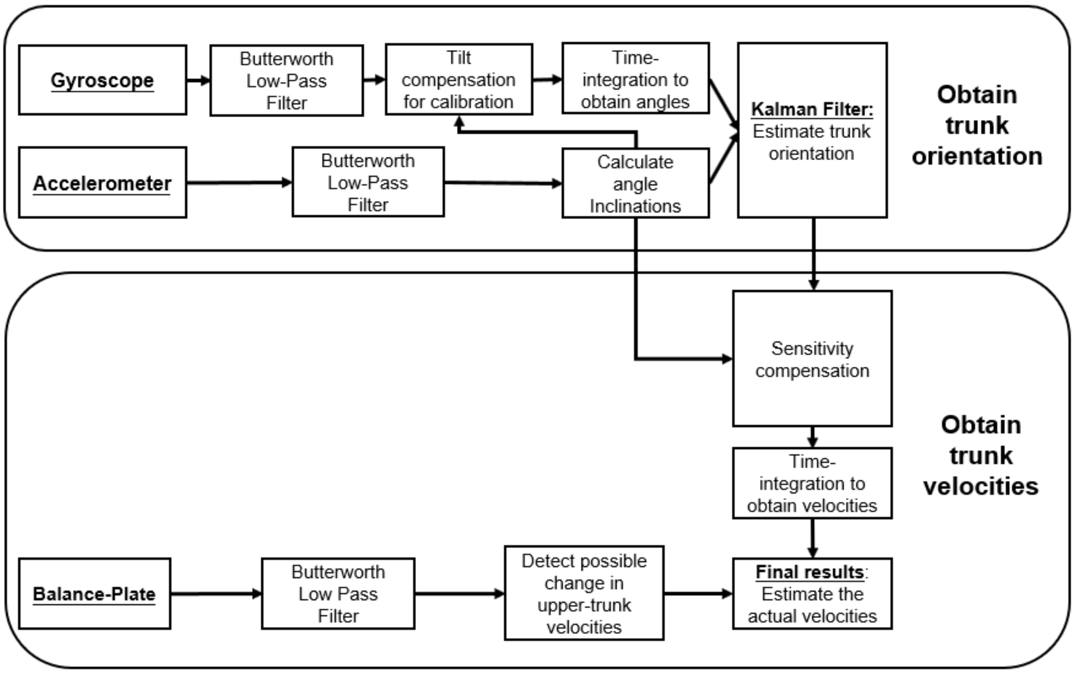


Figure 26: The new bespoke Kalman-filter based sensor fusion algorithm developed in this study.

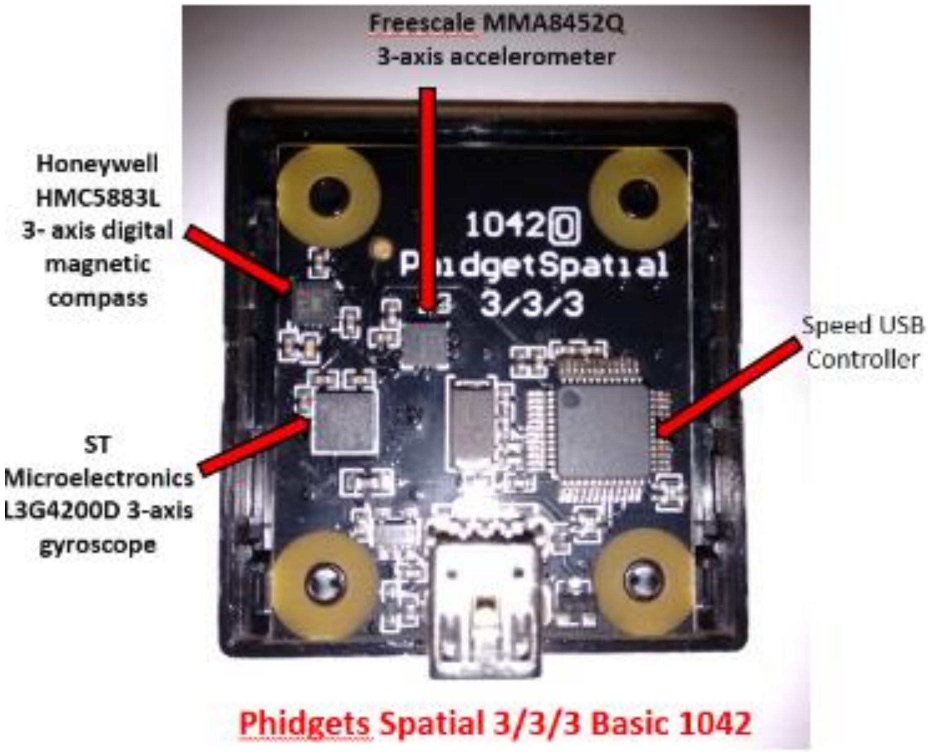


Figure 27: The inertial sensor (Phidgets Spatial 3/3/3 Basic 1042) adopted in this study.

An inertial sensor (PhidgetSpatial 3/3/3, Phidgets Inc., Calgary, Alberta, Canada), measuring three-axial accelerations and angular velocity (see figure 27), and a force plate (BP 50 Dual, Bertec Corp., Columbus, Ohio, U.S.A.) were adopted in this study. Their low-cost, good electrical characteristics, such as maximum swing, sensitivity and bandwidth, made them suitable for this study. Moreover, they fit the user requirements of portable, lightweight, ease-of-use and low-cost as indicated in section 3.3. See appendix 5 for their technical details.

Firstly, the accelerometer and gyroscopic signals were filtered by a second-order Butterworth low-pass filter to remove different types of oscillations and noises that were causing unwanted frequency components in the sampling spectrum. The cut-off frequency applied to the filters were at 11 Hz, a frequency that has been used in similar STS movement research (Matsumoto & Griffin, 1998). The body tilt angle at rest was calculated from the accelerometer signals to calibrate the gyroscope by defining the initial rotation angles with respect to the global reference frame. Because the body was at rest, therefore, it was assumed that the dynamic acceleration was zero. Later the estimated tile angles are fetched to a custom designed Kalman-filter for data fusion and errors removal.

4.2.1 Design of the Kalman-Based Sensor-Fusion Algorithm

A Kalman filter can be represented by a state-space model, as shown in figure 28, to indicate different inputs, outputs and variables involved in the system, and their values vary from time-to-time.

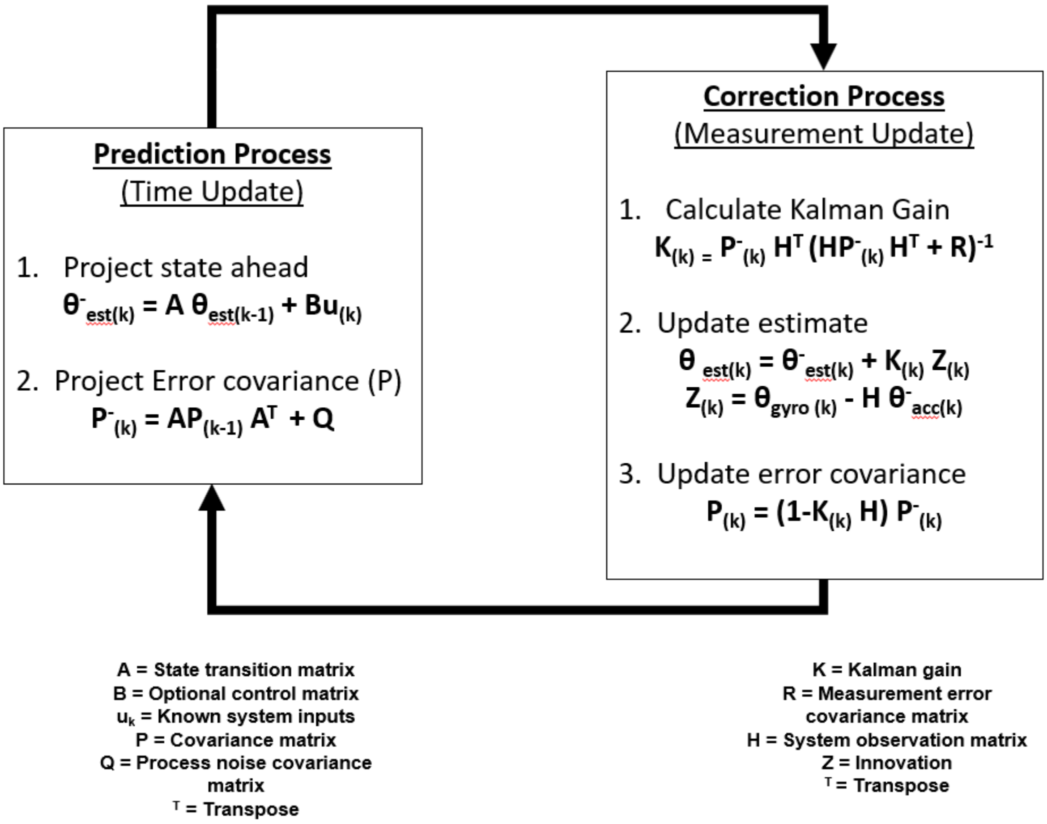


Figure 28: The Kalman filter algorithm developed in this study for estimating angles using raw data from a gyroscope and an accelerometer.

4.2.1.1 Project State Ahead

When a Kalman filter operates, it starts with its state predication process:

$$\theta^{-}_{est(k)} = A\,\theta_{est(k-1)} + Bu_{(\boldsymbol{k})}$$

$\theta^{-}_{est(k)}$ is a state vector. It contains the term of interest, in this case, the angle being estimated by the Kalman filter and is defined as the priori state hypothesised and predicted at time, k. $\theta_{est(k-1)}$ defines the posteriori state of the measured angle obtained by the system's observation at time, k-1.

A is a state transition matrix. It multiplies the state vector and maps its effects, if any, onto the state vector, in this case, the estimated angle from time, k-1 to time, k. In this study, A is equal to 1. $u_{(k)}$ is a control input vector. It considers input signals which could affect the estimated angle, in this case, there are two inputs, biases in the gyroscopic signals due to drifts and errors, and the actual angular velocity. B is a control input transition matrix. Similar to A, it maps its effects onto the control input vector from the previous cycle time, k, to the next cycle time, k-1. In this study, B is defined as “dt”, the sampling period, as the estimated angle is equivalent to the sampling period multiplied by the angular velocity.

4.2.1.2 Project Error Covariance

P is a covariance matrix. It contains the latest estimate of the average errors in the measurements. Initially, when the system starts, the value of the matrix is zero. As the Kalman filter executes, the values will change. Eventually, it will converge and reach a steady state and does not depend on any more measurements. The diagonal elements of P are the variances of the variables in Q, an estimated process error covariance, which contains the estimated angle and angular velocity. The values of the error covariance are pre-defined.

4.2.1.3 Kalman Gain

The Kalman gain, represented as K, moderates the system's prediction. It determines the amount of correction needed to be applied to the incoming measurements, in order to remove the errors and produce the most accurate estimations. As the Kalman filter iterates, the Kalman gain increases. This implies that the "amount of corrections" applied to the noisy measurements is increasing. H is a system observation matrix. It allows the prediction and measurements to be multiplied together. R is a measurement error covariance matrix. Both H and R regulate the Kalman gain.

4.2.1.4 Update Estimate

The estimated angle is dependent on the Kalman's innovation, $Z_{(k)}$. The innovation, also known as the system residue, is the measurement estimated errors. In the designed Kalman filter, it is the angle estimated by time-integrating the gyroscopic signals minus the angle estimated by the accelerometer. Then, it is multiplied by the Kalman gain and updates the system's estimated angle based on the best available prediction in the system model.

4.2.1.5 Update Error Covariance

Lastly, the error covariance is updated based on the latest Kalman gain. The error covariance will be amended when the Kalman filter executes the prediction process again.

4.2.1.6 Sensitivity Compensation

The sensitivity of accelerometers varies according to its inclination angles (see figure 29). For instance, when the z-axis of accelerometers tilted and orthogonal to the direction of the force of gravity, its sensitivity drops to zero and vice versa, when it tilted and in parallel to gravity, its sensitivity peaks. However, if the titled angle is known, the sensitivity issues with the acceleration signals could be compensated using trigonometry (Łuczak, 2014):

$$a_{compensated} = \frac{a_{actual}}{\cos\theta}$$

In this sensor-fusion algorithm, the angle is the estimated angle from the Kalman filter. As the compensated acceleration data will be time-integrated to derive the linear velocity, if this piece of information is not accurate, significant errors and drifts will accumulate in the estimated velocity.

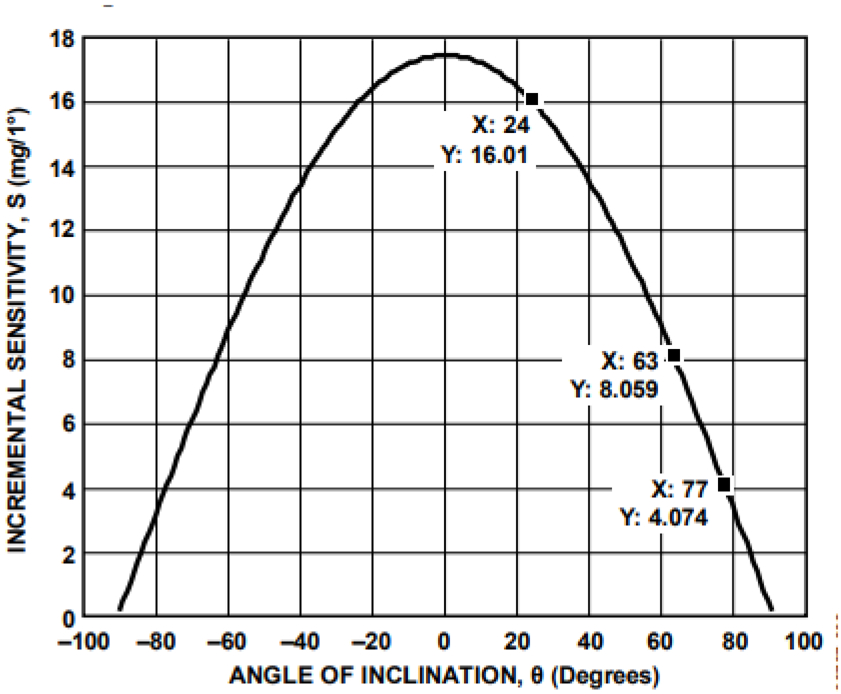


Figure 29: The changes to the accelerometer sensitivity in the Y plane when it tilted at different angles in the X plane.

4.2.1.7 Involvement of a Force Plate

The force data obtained from the force plate were also Butterworth low-pass filtered at 11 Hz, a frequency that has been used in similar STS movement research (Matsumoto & Griffin, 1998), to remove high-frequency noise. If a change in the signal was detected, time-integration would be achieved in real-time to obtain upper-trunk velocities with the compensated accelerations. This error-compensation technique prevents long-term integration drifts that could occur for various reasons (e.g. temperature fluctuations, external vibration, hysteresis and non-linearity) and causing the velocity estimation to become unusable and drift from its true value within a few seconds.

4.2.2 Adaptive Algorithm for Detecting Phases and Timing

The processed kinematic data were then fetched to an STS detection algorithm. This adaptive algorithm analyses and detects crucial events, transitions between phases and timing of the STS movement dedicated to geriatric population as discussed in section 2.4.

This was modelled using a finite state machine (W. Kerr, Tran, & Cohen, 2011), a mathematical computation tool to demonstrate the sequential logic in detecting STS phases. This dedicated computational tool is commonly used in system control and implementation and graphically display the use of limited processing resources for complex and flexible systems (Drumea & Popescu, 2004). This is especially important for real-time applications, such as this study.

The finite state machine has four components:

1. A set of possible input signals,
2. A set of possible states,
3. A set of possible transitions between all states,
4. A set of system actions performed when each state is triggered.

This algorithm differentiates the dynamics of getting up from a sitting position to reaching a standing position into four states by analysing upper trunk motion and GRF generated during the movement (see figure 30). Each state represents a phase of the STS transfer. The algorithm starts at “Phase 0”. At the same time, the user remains seated in a sitting position before activating the movement. When the force plate detects the user’s feet weight and if the upper trunk moved forward by 5°, trying to generate the initial momentum required for rising, “Phase 1” is activated. If the plate does not detect the user feet weight, it suggests the user’s feet are not on the plate and returns to “Phase 0”.

When the user is trying to stand-up, the push-forward momentum is then transferred to upward momentum from the upper trunk to the whole body. This is detected as the trunk angle increases and “Phase 2” is then activated. However, if the user was returning to the chair as detected by a drop in measured weight and trunk angle, “Phase 1” is activated again.

At “Phase 2”, if the user continues to lean forward until the upper trunk reaches 30° and the body weight is detected by the force plate, “Phase 3” is reached. However, if the trunk angle and weight dropped, “Phase 1” will then be activated.

During “Phase 3”, the trunk, knees and hips extend, the body rises as the trunk angle returns to 0° until it is stabilised and stand-up straight at “Phase 4”. If the user returns to the chair, their weight measured by the force plate will drop, and the end phase will then be triggered. The system then returns to “Phase 0” and the algorithm will repeat from the beginning. Please refer to table 8 for further details.

Figure 30: A finite state machine chart showing the adaptive algorithm in analysing the STS transitions.

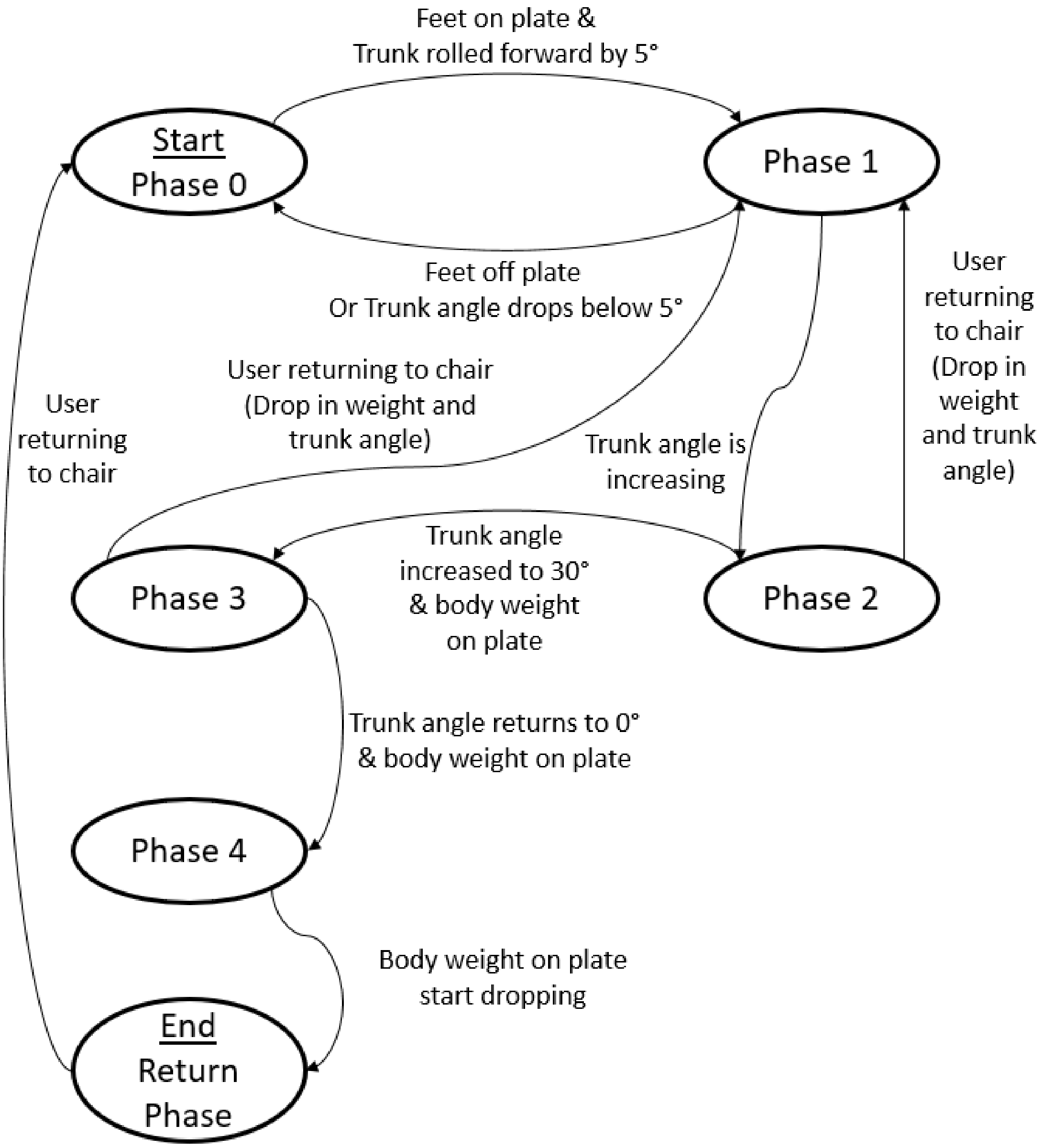


Table 8: A state transition table showing the implementation of the finite state machine for detecting STS events.

Present state	**Inputs**		**Next state**
	Trunk Roll Angle (degrees)	***Vertical Ground Reaction Force***	***(Defined STS phase)***
Start: Phase 0 (Sitting)	Any	< Feet weight	Stay at Phase 0
Phase 0 (Sitting)	<5	Any	Stay at Phase 0
Phase 0 (Sitting)	≥ 5	≥ Feet weight	Phase 1
Phase 1 (Flexion momentum)	< 5	Any	Phase 0
Phase 1 (Flexion momentum)	Any	< Feet weight	Phase 0
Phase 1 (Flexion momentum)	≥ 5 and <30	≥ Feet weight	Stay at Phase 1
Phase 1 (Flexion momentum)	≥ 30	≥ Feet weight	Phase 2
Phase 2 (Momentum transfer)	Any	< Body Weight	Phase 1
Phase 2 (Momentum transfer)	≥ 30	< Body weight	Phase 1
Phase 2 (Momentum transfer)	≥ 15 and <30	≥ Body Weight	Stay at phase 2
Phase 2 (Momentum transfer)	< 15	≥ Body Weight	Phase 3
Phase 3 (Extension)	> 15	≥ Body Weight	Phase 2
Phase 3 (Extension)	Any	< Body Weight	Phase 1
Phase 3 (Extension)	≥ 5 and <15	≥ Body Weight	Stay at phase 3
Phase 3 (Extension)	< 5	≥ Body Weight	Phase 4
Phase 4 (Standing)	Any	≥ Body Weight	Stay at Phase 4
Phase 4 (Standing)	Any	< Body Weight	Phase 0

4.2.3 Geriatric Participant Testing

In order to verify the performance of the developed algorithms, five mobility-impaired older adults were invited to a biomechanical laboratory at the University of Strathclyde, for a trial. They were recruited from a Chest Heart and Stroke Scotland support group and were given the participant information sheets at least seven days in advance of the appointment at the university (see appendix 1).

Firstly, the researcher explained the study and a consent form was signed by the participants. They were assessed with the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005) (see appendix 6) in which all passed with a score above 26 and deemed to have a normal cognitive ability (Nasreddine et al., 2005). Their height and weight were measured. Their difficulties in standing-up were asked and recorded. The participants were then seated on a standard chair (the chair height was 49.5 cm) in an upright position with their back touching the seatback. The chair has a pair of armrests which could be used for support if needed. Their feet were placed on the force plate.

A vest was put onto the participant's upper trunk (see figure 31). The inertial sensor was placed into a pocket on the vest located near the sternum, which is more sensitive to upper trunk vertical and horizontal velocities and trunk rotations than other areas of the body (Zampieri et al., 2010). Five reflective markers were then attached directly on the inertial sensor (see figure 32).

The movements of the reflective markers were recorded by the Vicon motion capture system with motion capture software, Nexus 2.6 (Vicon Motion Systems Ltd UK, Oxford, U.K.). The three-dimensional coordinates (X, Y and Z) of each marker when the participant was standing up is recorded at 50 Hz. The real-time kinematic data processed by the sensor fusion algorithm were also captured at 50 Hz by a system design platform (LabVIEW 2013 Service Pack 1, National Instruments Corp., Austin, Texas, U.S.A). The data were exported to a spreadsheet file and processed in MATLAB 2012b (MathWorks Inc., Natick, Massachusetts, U.S.A.).

The whole-body model with plug-in gait model was used. The movements of the reflective markers were also recorded by the Vicon motion capture system with motion capture software, Nexus 2.6 (Vicon Motion Systems Ltd UK, Oxford, U.K.). The three-dimensional coordinates (X, Y and Z) of each marker when the participant was standing up is recorded at 50 Hz. The real-time kinematic data processed by the sensor fusion algorithm were also captured at 50 Hz by a system design platform (LabVIEW 2013 Service Pack 1, National Instruments Corp., Austin, Texas, U.S.A). The data were exported to a spreadsheet file and processed in MATLAB 2012b (MathWorks Inc., Natick, Massachusetts, U.S.A.).

Using trigonometry, the pitch angle and roll angle of the inertial sensor could be calculated from the coordinates of the top marker and bottom marker. This could then be compared to the angles measured by the sensor-fusion algorithm. The vertical velocity of the inertial sensor was calculated by working out the difference of its initial y-position and its final y-position between each sampling interval from the coordinates obtained. The data could also be compared to the velocity obtained from the sensor-fusion algorithm.

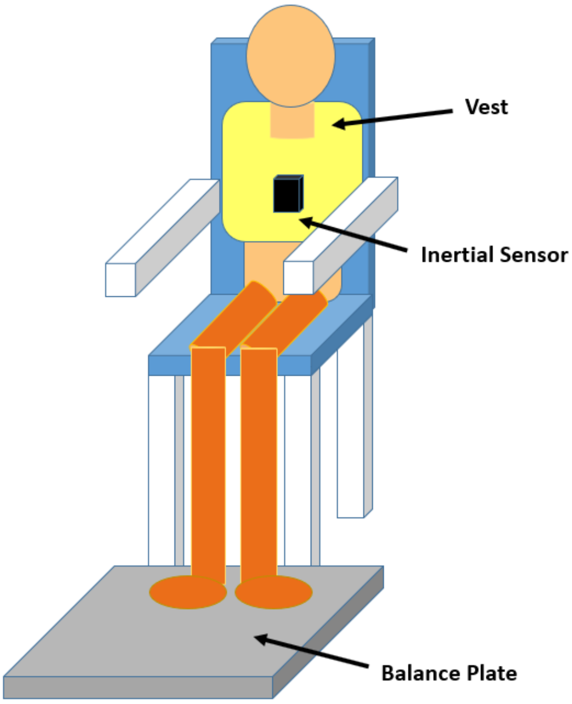


Figure 31: The system's set up, showing a "participant" wearing a vest, sitting on a standard chair while both feet are on the force-plate.

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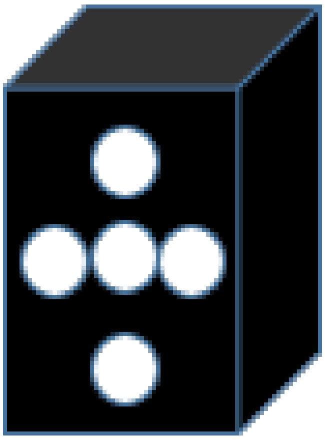


Figure 32: The positions of the five reflective markers on the inertial sensor.

$$Pitch\ angle = \tan^{-1}\frac{Z_{top\ marker} - Z_{bottom\ marker}}{Y_{top\ marker} - Y_{bottom\ marker}}$$

$$Roll\ angle = \tan^{-1}\frac{X_{top\ marker} - X_{bottom\ marker}}{Y_{top\ marker} - Y_{bottom\ marker}}$$

$$Vertical\ Velocity = \frac{Y_{final} - Y_{initial}}{t_{sample}}$$

Table 9: Demographic information and characteristics of the geriatric participants.

Age (Years) Mean (S.D.)	70.2 (6.30)
Gender M/F	3/2
Weight (kg) Mean (S.D.)	72.6 (9.61)
Height (cm) Mean (S.D.)	168 (6.02)
Comorbidity	All five geriatric participants suffered from strokes. Three participants diagnosed with arthritis and affected their knees. Another participant suffered from chronic back pain.

4.3 Results

The real-time kinematic data processed by the sensor-fusion algorithm was verified by the data from the Vicon system. The estimated rotational angles and vertical velocity obtained from the developed sensor-fusion algorithm were closely matched with the recorded Vicon data (see figure 35). The Vicon data was filtered by a Butterworth low-pass filter with a cut-off frequency of 11 Hz, same as the low-pass filtering process adopted for the sensor-fusion algorithm.

The mean values of the measured STS kinematics were calculated as Regterschot, et al (2014) demonstrated that using the means of five STS repetitions in statistical analysis have the highest test-retest reliability for STS kinematics captured by electronic sensors. During the feasibility testing, not all geriatric participants were able to complete five repetitions, but the mean values were still calculated based on the captured data from all five participants.

The mean trunk lean forward (roll) angle obtained by the sensor-fusion algorithm was 18.7 degrees, while the mean roll angle measured by the Vicon system was 21.5 degrees as shown in figure 37. Therefore, the mean error in the estimated roll angle was 2.8 degrees. This is an improvement compared to the accelerometer-only method (average error of 8.1 degrees) and gyroscope-only method (average error of 5.2 degrees). The mean error when measuring the peak roll angle was 4.5 degree.

The same calculations were repeated for the trunk lateral bending (pitch) angle. The mean pitch angle obtained by the sensor-fusion algorithm was 8.6 degrees, while the mean pitch angle measured by the Vicon system was 10.3 degrees as shown in figure 38. Therefore, the mean error in the estimated pitch angle was 1.7 degrees. This error is much lower than the measurements obtained from the accelerometer-only method and gyroscope-only method respectively, 7.9 degrees and 4.2 degrees. The mean error when measuring the peak pitch angle was 2.1 degrees. There is a delay of about 0.1 seconds when estimating angles, which is not important for providing feedback and is acceptable for signal processing (Alam & Rohac, 2015).

The mean vertical velocity estimated by the sensor-fusion algorithm was 0.278 ms^{-1} compared to 0.375 ms^{-1} which was the mean of the vertical velocity measure by the Vicon system as shown in figure 39. Therefore, the mean error is 0.094 ms^{-1}. The mean error in estimating the peak vertical velocity was 0.137 ms^{-1}.

The comparison shows a small systematic bias as the mean and peak vertical velocity processed by the algorithm were lower (on average) compared with the Vicon measurements when the velocity reaches its peak. However, this bias was illegible in readings that were captured from participants with slower STS executions.

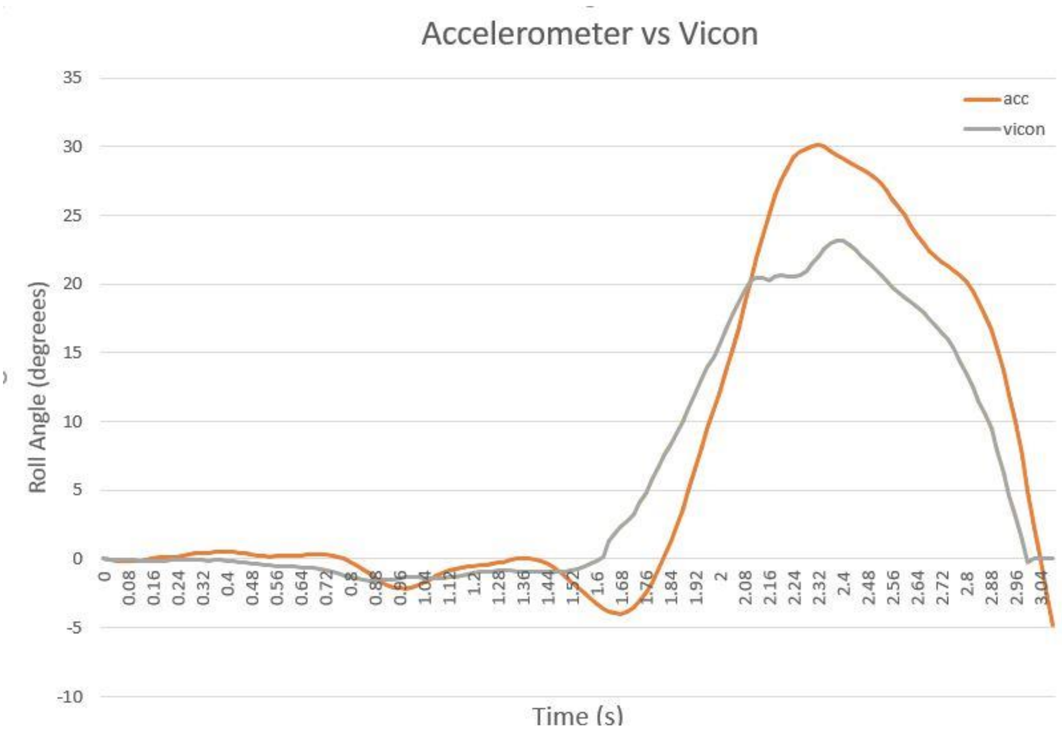


Figure 33: Roll angles (trunk lean forward angle) measured by the accelerometer and Vicon on a participant without the use of the developed sensor-fusion algorithm.

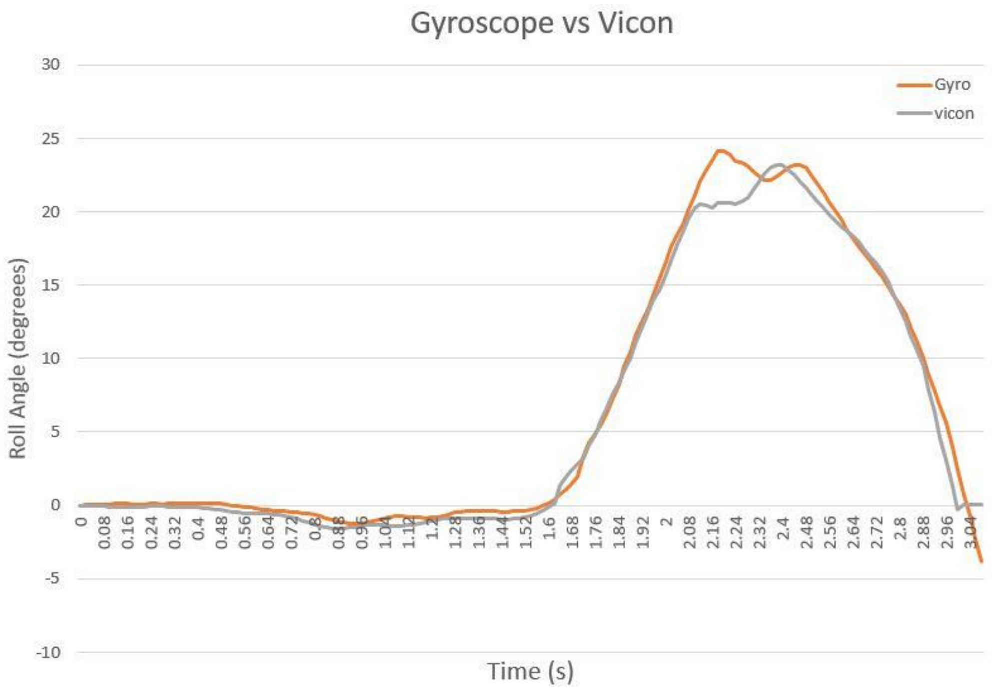


Figure 35: Roll angles (trunk lean forward angle) measured by the gyroscope and Vicon on a participant without the use of the developed sensor-fusion algorithm.

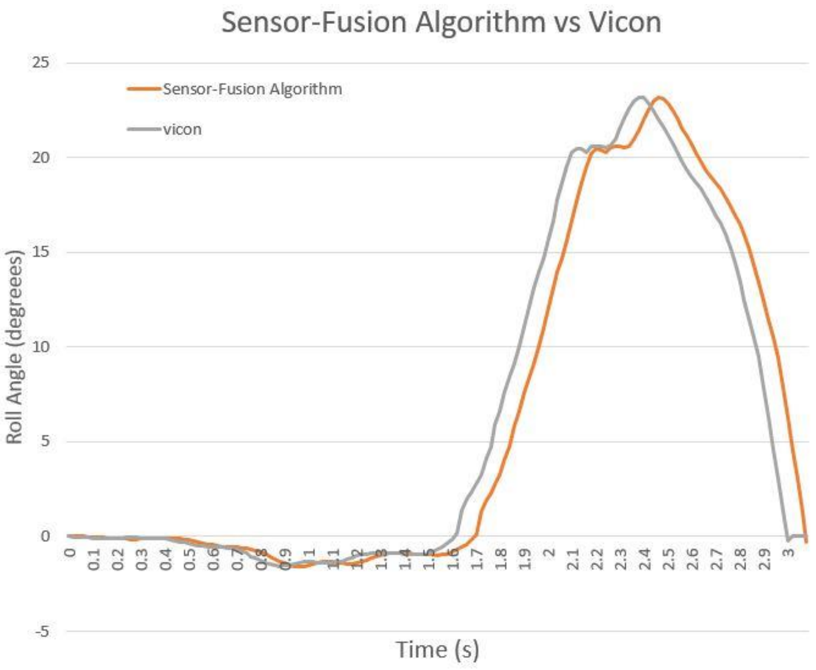


Figure 34: Roll angles (trunk lean forward angle) estimated by the developed sensor-fusion algorithm and Vicon on a participant.

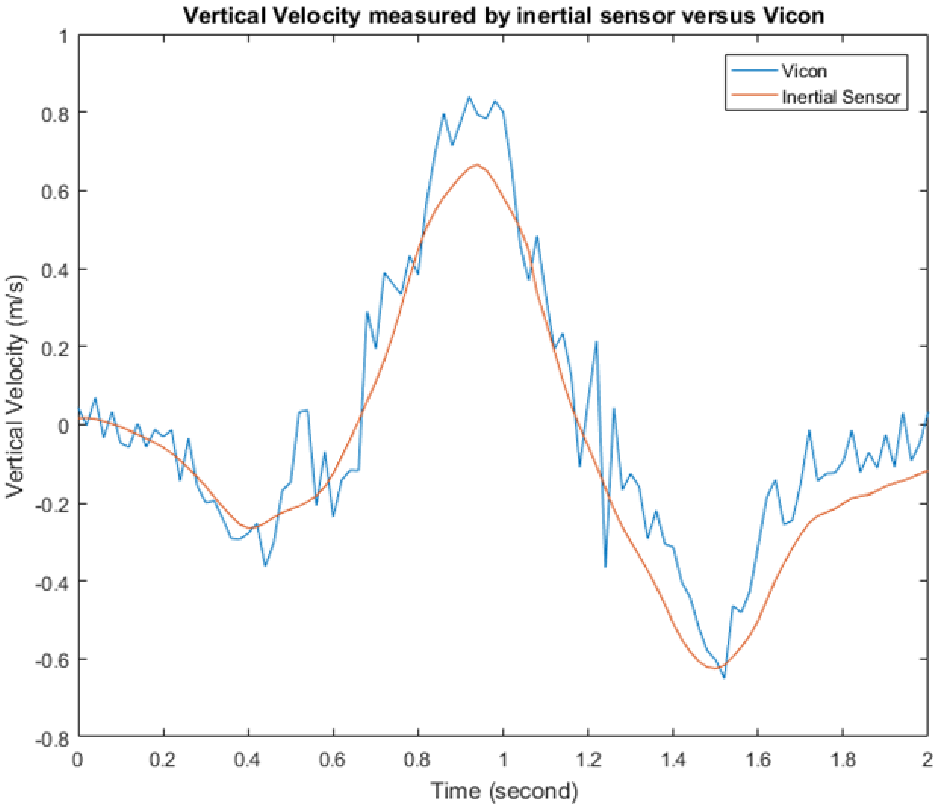


Figure 36: Vertical velocity estimated by the developed sensor-fusion algorithm and Vicon on a participant.

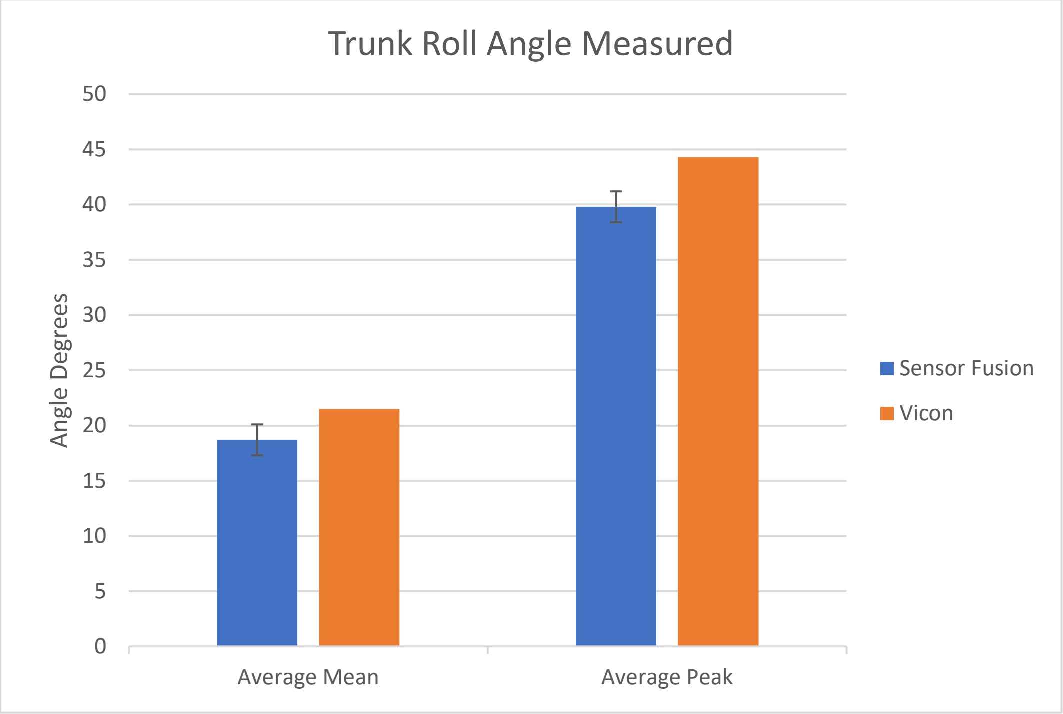


Figure 37: Showing the average mean and average peak trunk roll angle measured by the sensor-fusion algorithm.

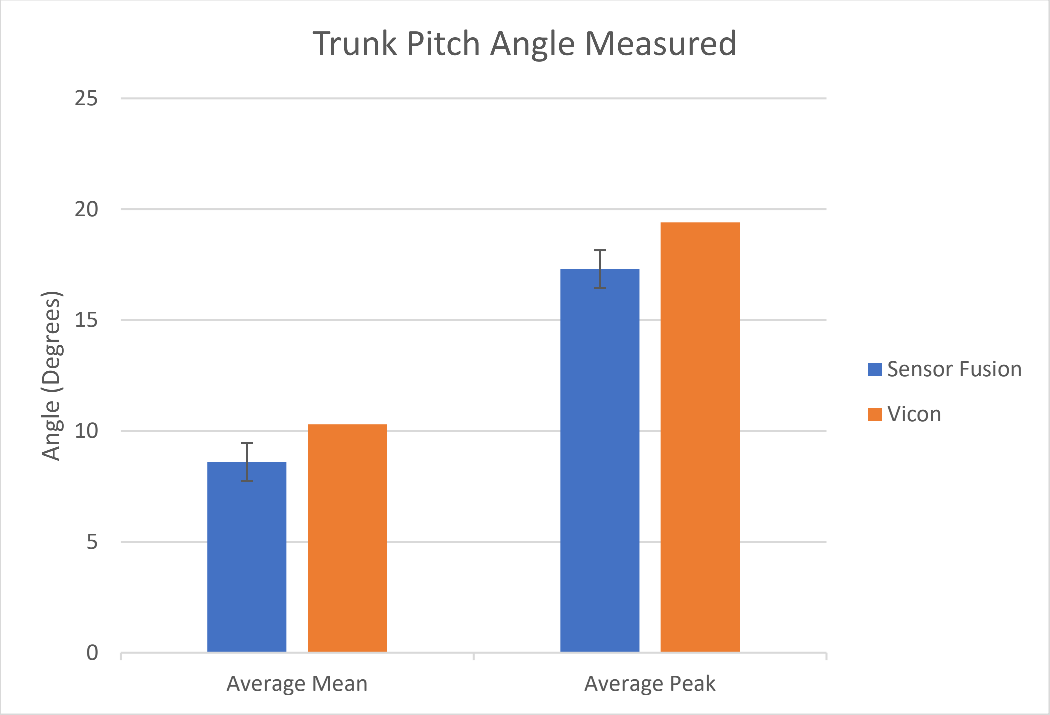


Figure 38: Showing the average mean and average peak trunk pitch angle measured by the sensor-fusion algorithm.

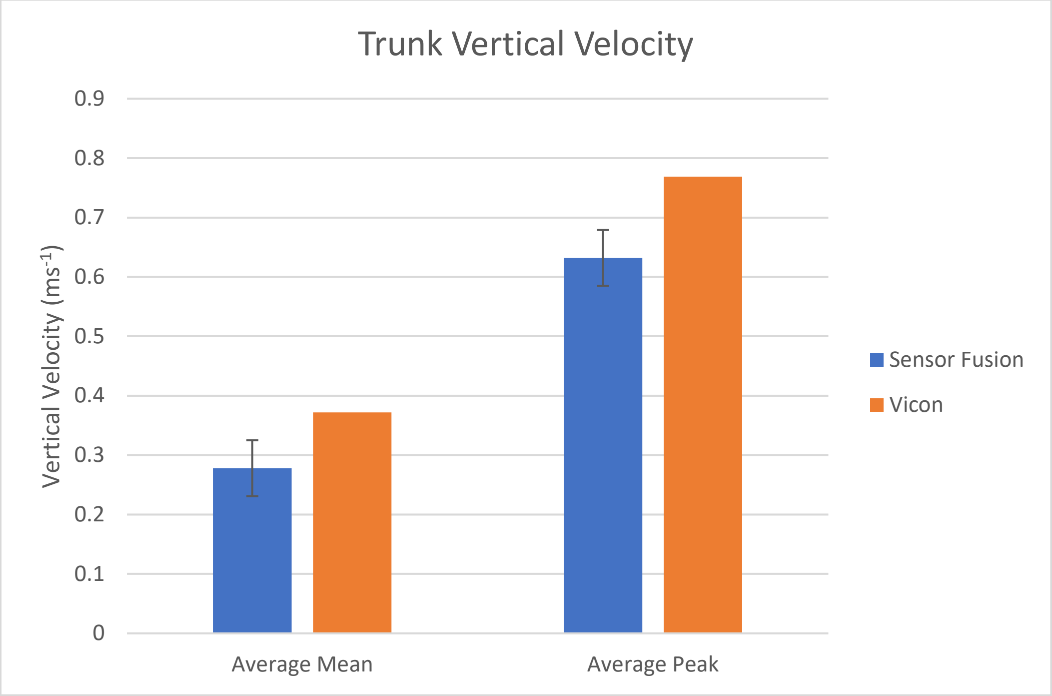


Figure 39: Showing the average mean and average peak trunk vertical velocity measured by the sensor-fusion algorithm.

The real-time STS detection algorithm has successfully determined all four phases of the STS movements in all trials with a small overestimation of time and consistent delay in detecting the transition of phases (see figure 40). As detected by the adaptive algorithm, the mean time of phase 1 was 1.19 seconds compared to 1.02 seconds as observed using the upper-trunk plug-in-gait model. This introduced a mean error of 0.17 seconds in estimating phase 1. The mean time of phase 2 was 0.82 seconds as detected by the adaptive algorithm compared to 1.03 seconds as observed using the upper-trunk plug-in-gait model. The mean error, therefore, is 0.21 seconds. For phase 3, the mean time was 0.74 seconds as detected by the adaptive algorithm and 0.89 seconds as observed using the Vicon system. This gives a mean error of 0.15 seconds.

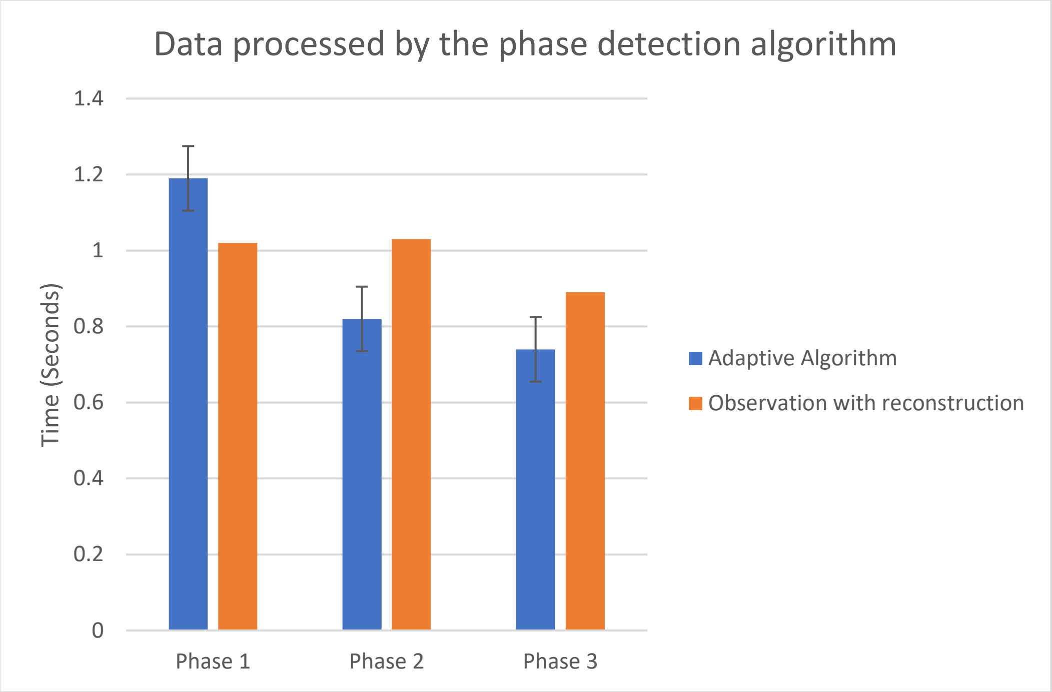


Figure 40: Showing the mean time of each detected STS phase using the adaptive algorithm and Vicon reconstruction.

Table 10: Comparison between the data processed by the developed algorithms and measurements recorded by Vicon. The data were combined from the five trials.

Parameters	**Senor Fusion**		**Vicon**		**Magnitude of Errors**	
	Average Mean	***Average Peak***	***Average Mean***	***Average Peak***	***Average Mean***	***Maximum Error***
Trunk Roll (degrees)	18.7	39.8	21.5	44.3	2.8	4.5
Trunk Pitch (degrees)	8.6	17.3	10.3	19.4	1.7	2.1
Trunk Vertical Velocity at Peak (ms^{-1})	0.278	0.632	0.372	0.769	0.094	0.137
	Adaptive Algorithm		***Observation with reconstruction***		***Magnitude of Errors***	
Phase 1 of STS (seconds)	1.19		1.02		0.17	
Phase 2 of STS (seconds)	0.82		1.03		0.21	
Phase 3 of STS (seconds)	0.74		0.89		0.15	

4.4 Discussion

This study proposed a new measurement approach of using a low-cost wearable inertial sensor and a portable force plate for tracking the STS movement in mobility-impaired individuals in the geriatric population. It combines a bespoke sensor-fusion algorithm and an adaptive algorithm in detecting and analysing the motion. The was based on the need for a clinical feedback system to support practise of the STS movement during rehabilitation.

The results demonstrate the developed sensor-fusion algorithm is effective when dealing with inertial sensors' weaknesses, such as integration drifts when measuring angles and velocities. Its performance in estimating the quantities is superior to using an accelerometer or a gyroscope alone.

The erroneous readings due to integration drifts and temperature drifts were greatly reduced. For instance, using only an accelerometer in estimating the trunk lean forward (roll) angle introduced a maximum error of 10 degrees as shown in figure 33 and an error of 6 degrees when using a gyroscope only, as shown in figure 34. The finding implies the values of the noise covariances (Q and R) chosen for this Kalman filter were suitable for this specific inertial sensor adopted in this study and they are accurate when dealing with STS movement in geriatric population. Most importantly, this algorithm could comfortably be used in real-time in detecting the motion using a low-cost computer with low computation resources.

The errors in estimating angles and velocity were lower than other studies on sensor-fusion algorithms when measuring movements which are using high-cost high-quality inertial sensors (Anjum et al., 2010) (El-Gohary & McNames, 2015). This implies the accuracy and precision of the bespoke algorithm implemented in this study has great potential to be adopted in other areas of rehabilitation. The STS detection algorithm was capable of detecting each phase of the STS movement, 100% of the time in the five trials.

However, the sensor-fusion algorithm could not totally reduce the errors due to drifting when estimating velocity as shown in figure 34. This was due to the sensitivity issues could not be completely compensated as ideal characteristics were assumed. Both algorithms provide promising results when estimating and analysing the STS movement in geriatric patients. However, other geriatric patients could have different STS characteristics such as standing much slower. This study has been tested on five participants who were sitting on the same type of chair. More participants and trials are needed to see whether these algorithms could be applied to a larger population and different types of chair.

Incorporating a magnetometer into the sensor-fusion algorithm could help to improve estimations (Ciuti et al., 2015). Although they do not affect the estimated angles, however, the issues with singularities do present in this design. The use of quaternion number system could potentially resolve these issues (Valenti, Dryanovski, & Xiao, 2015).

It was found that the inertial sensor was suitable for real-time capturing of 3D upper trunk kinematics. This fits the conceptual design attributes (portable wearable technology) as stated in section 3.2.2.2. The original two concepts for wearing the sensor, however, created technical challenges. The first concept was having a hooks and loops strap placed across the chest. In practice, it might be uncomfortable for some users. The second concept was having an adjustable belt and buckle strap placed around the shoulders, however, less able users may find it difficult to put the strap on or off themselves. Therefore, the design was refined and a vest, which could be put on and off with one hand, was adopted instead. Moreover, the data gathered in this chapter has impacted on the detailed design of the system. In this case, a unique sensor-fusion algorithm was developed according to the user-requirements as defined in section 3.2.3.2.

The adaptive algorithm introduced a delay. The exact empirical values for how long a delay is acceptable when playing a rehabilitation game is difficult to find. However, most individuals would hardly able to notice a delay when playing a virtual reality game as short (Raaen & Kjellmo, 2018) as the one produced by the adaptive algorithm.

4.5 Summary

In this chapter, a new sensor-fusion algorithm and an STS detection algorithm were proposed for detecting and analysing the STS movement in physically impaired older adults. The sensor-fusion algorithm was based on a Kalman-filter. It processes raw signals fetched from a low-cost inertial sensor (i.e. accelerometer and gyroscope) and a portable force plate in estimating real-time trunk angles and velocities. The STS detection algorithm, which was built on a finite state machine, derives real-time crucial events, the transition between phases and timing of the STS movement.

A trial was conducted on five geriatric participants to test the performance of the algorithms against a gold-standard motion capture system. The sensor-fusion algorithm could eliminate non-ideal characteristics of the inertial sensor in estimating real-time angles and velocities, such as integration drifts. The STS detection algorithm detected all STS phase changes in real-time. The bespoke algorithms can be adopted in this study to produce performance feedback.

Chapter 5 – Generation of Feedback

5.1 Introduction

After algorithms for capturing the motion data and detecting the STS movement were developed and validated with five geriatric patients, as discussed in chapter 4, the thesis will now focus on generating feedback on STS performance based on the acquired kinematic data.

The importance of feedback to motor learning was discussed in chapter 2, section 2.6. The aim of this chapter is to discuss the development and evaluate the feasibility of a feedback platform for delivering extrinsic feedback for training the movement in older adults. This will include discussions on the implementation of a fuzzy-logic based automated feedback generation system (AFGS) and a visual feedback system (VFS) for presenting the feedback both visually and auditory in a virtual reality (VR) environment. A feasibility study was conducted with mobility-impaired older adults to assess the practicality of the proposed platform. The findings are also presented and discussed in this chapter.

5.2 The Importance of Feedback

Providing feedback, informing users of their performance, such as what and how to enhance their movements, can improve their rehabilitation experience while reducing the time for recovery (Liebermann et al., 2006) (Abe et al., 2011). This has been established by researchers which shows patients were more motivated and spent more time practising if feedback was delivered

(Stanton et al., 2015). However, many geriatric patients do not receive adequate therapy services due to limited staffing and funding cuts (Stroke U.K., 2016).

As discussed in section 2.7.2.2, VR based rehabilitation system stimulates the user’s physical presence in an artificially replicated real-world setting. It has emerged as a new training environment. Immersive VR environments have demonstrated to be more effective than standard therapy (Laver et al., 2018) as they have a positive influence on motivational aspects of motor recovery while maximising training time with adequate visual and auditory feedback (Corbetta, Imeri, & Gatti, 2015). Moreover, they increase user concentration, incentive, intensity and frequency of practice by reproducing computerised real-world situations (Corbetta, Imeri, & Gatti, 2015). VR is considered as an alternative intervention for regaining ability of activities of daily living (Kim, Lee, Kim, Eun, & Yoon, 2016). Therefore, a VR environment was developed in this study, to provide visual and auditory feedback for training the STS movement.

In order to deliver extrinsic feedback to users through VR, an automated feedback generation system (AFGS) was implemented for functional evaluation of the STS movement in older adults. This system analysed the processed kinematic data from the sensor-fusion algorithm and STS transitions from the STS detection algorithm (see section 4.2), and generated feedback accordingly. After that, a visual feedback system (VFS) was developed to present the generated real-time feedback visually and auditory in a VR environment.

5.3 Implementation of an Automated Feedback Generation System

The AFGS was based on a fuzzy inference system (FIS). This proposed system was aiming at delivering feedback usually provided by therapists in real-time and at the end of training. Due to the needs for a highly effective and efficient computation model to generate human-like feedback, FIS was considered.

It evaluated STS performance by accomplishing input-output mapping based on sets of rules in a knowledge base. FIS's describe the system's values of attributes as degrees of likelihood. Compared to conventional Boolean logic, this characteristic established an advantage in dealing with uncertainties and vagueness, it is considered to be similar to the human decision-making process, and is often encountered in fields of medical applications (Torres & Nieto, 2006) (Gürsel, 2016).

FIS's use fuzzy logic, which was first introduced by Zadeh in 1965 as a method of modelling human reasoning in artificial intelligence (Rosyara, Vromman, & Duveiller, 2008). Traditionally, hard computing logic provides two Boolean values, true or false (i.e. 0 and 1), for all decision-making processes. However, in the real world, when a human communicates, rationalises and makes decisions, there are more ambiguities and uncertainties than just two binary values (Sajfert, Atanasković, Pamučar, & Nikolić, 2012).

Fuzzy logic offers infinitely many-valued logics within a range of degrees of likelihood, from 0 (false) to 1 (true) (see figure 41). This reflects the indeterminacy of human reasoning that involved all possibilities (Haack, 1979). For instance, rather providing a definite Yes or a definite No, human decisions may include other possible answers with different degrees of certainty of confidence, such as Possibly Yes, Uncertain and Possibly No.

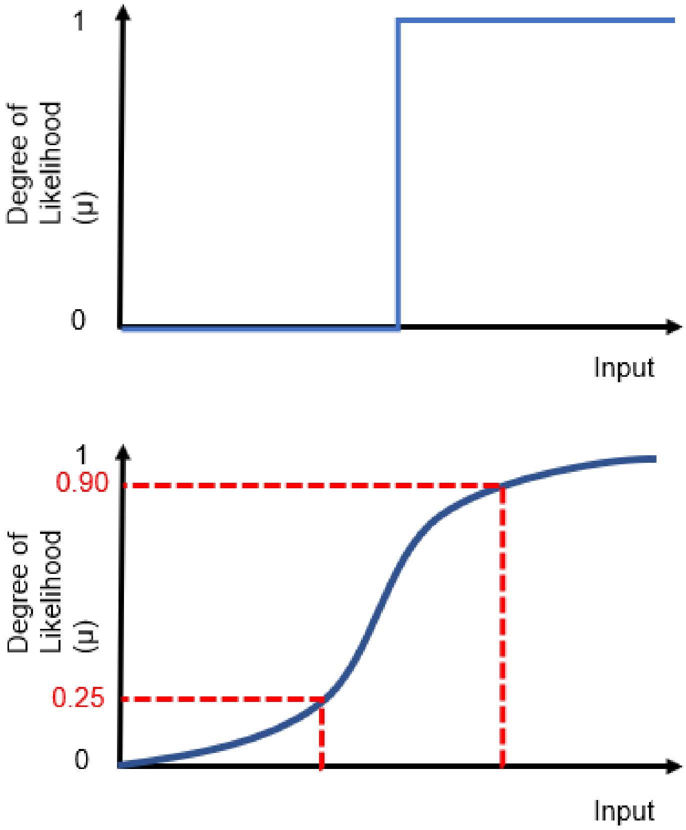


Figure 41: The top graph shows the outputs (0 and 1) of traditional Boolean logic. The bottom graph shows the infinitely many values representations of fuzzy logic.

Moreover, this decision-making technique has been demonstrated to have high efficiency as it does not require unwieldy computing resources and memory requirements of look-up tables and arithmetical demanding formula-based calculations (Z. Zhang, Fang, & Gu, 2014). In fact, FIS has been widely adopted in the fields of rehabilitation for example, in providing guidance of post-stroke physiotherapy exercises (Huq et al., 2013), classifying upper-limb motor functions (Tedim Cruz et al., 2014), defining human postures (Juang & Wang, 2015), classifying EMG signals when controlling prosthesis (F. H. Y. Chan, Yang, Lam, Zhang, & Parker, 2000), controlling mechanical feedback provided by a rehabilitation robot (Meng, Zhu, Zhou, Chen, & Ai, 2014) and predicting the risk of having Parkinson’s disease (S. Liu, Shen, McKeown, Leung, & Miao, 2014).

The system evaluated three principle functional factors to the successfulness of an STS movement in older adults as discussed in section 2.4;

- Force-symmetry;
- Impulse for push when rising,
- Trunk forward lean angle.

The range of values for these factors were identified from clinical studies which described them as the main key characteristics to successful or failed STS executions (Cheng et al., 1998) (Lomaglio & Eng, 2005) (Boukadida, Piotte, Dehail, & Nadeau, 2015b) (A. Kerr, Clark, & Pomeroy, 2018). Moreover, findings from questionnaires and interviews with therapists in the development process (section 3.2) also indicated that these three parameters are the key characteristics targeted during therapy in the functional evaluation of the STS movement. Therefore, the FIS was used to produce feedback on these three factors.

5.3.1 System Architecture

A fuzzy logic system consisted of four components:

- a fuzzification module,
- a knowledge base,
- a fuzzy inference engine,
- a defuzzification module.

5.3.2 Fuzzification

The fuzzification module maps the system inputs (kinematic data from the sensor-fusion algorithm), also known as crisp values, into sets of defined human language rules, called fuzzy logic sets. This process transfers the domain of the inputs from analogue into fuzzy values. Each of the inputs processed by the FIS has its own membership functions. These membership functions define the relationship between all possible input values and the degree of likelihood (DoL) within a range of 0 to 1, where 0 is definitely false, and 1 is definitely true. DoL is a fuzzy logic representation of the extent to which the linguistic value was met and represented in infinite gradations between absolute false (0) to absolute true (1) (Ali, Ali, & Sumait, 2015).

In this study, two membership functions were defined for each key STS evaluation factor. They were named as "good" or "bad" for each factor, and mapping the inputs as acquired from the sensor-fusion algorithm to the degrees of likelihood of a successful or failed STS movement. They are demonstrated in figure 42 to 47.

Table 11: Relationships between kinematics fetched to the AFGS and the types of the generated feedback.

Functional factors	**Crisp Inputs**	**Feedback**
Force-symmetry	• CoP in x-axis • Upper trunk lateral bending (pitch) angle	Real-time & Conclusive
Impulse for push when rising	• Peak upper-trunk vertical velocity • Peak GRF	Conclusive
Trunk forward lean angle	• Trunk lean (roll) angle • Stand-up time	Real-time & Conclusive

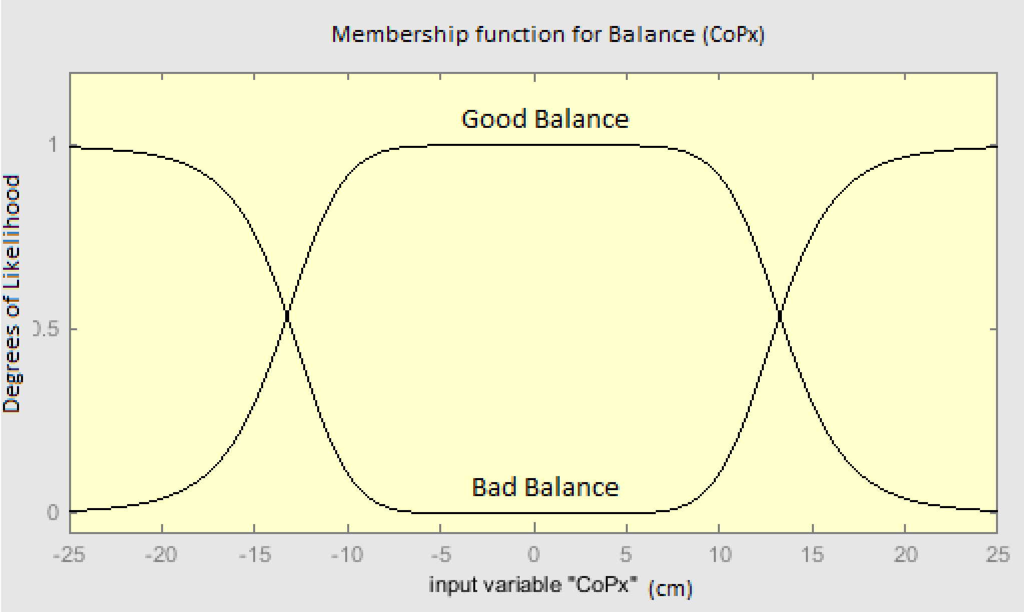


Figure 42: This figure shows the membership functions for mapping CoPx to the degrees of likelihood of good or bad force-symmetry, which would lead to a successful or a failed STS transfer.

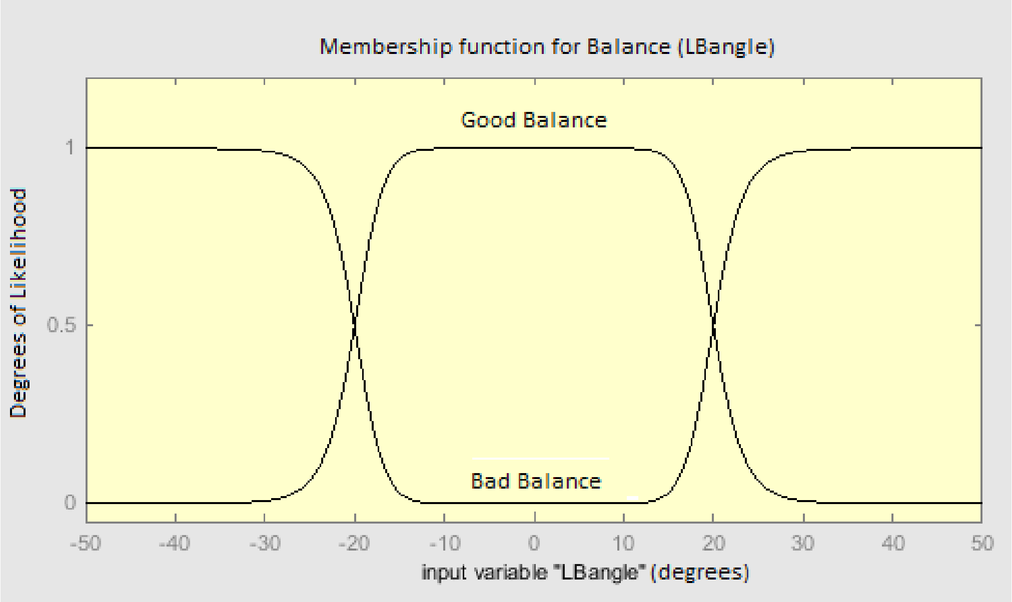


Figure 43: This figure shows the membership functions for mapping lateral bending (pitch) angle to the degrees of likelihood of good or bad force-symmetry.

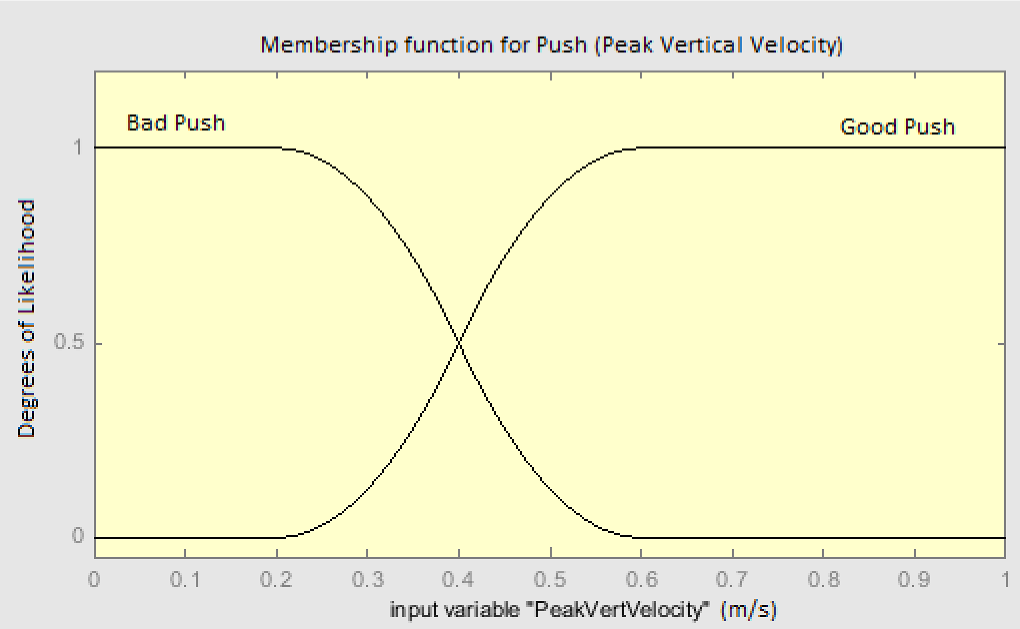


Figure 44: This figure shows the membership functions for mapping peak vertical velocity to the degrees of likelihood of a good or bad push.

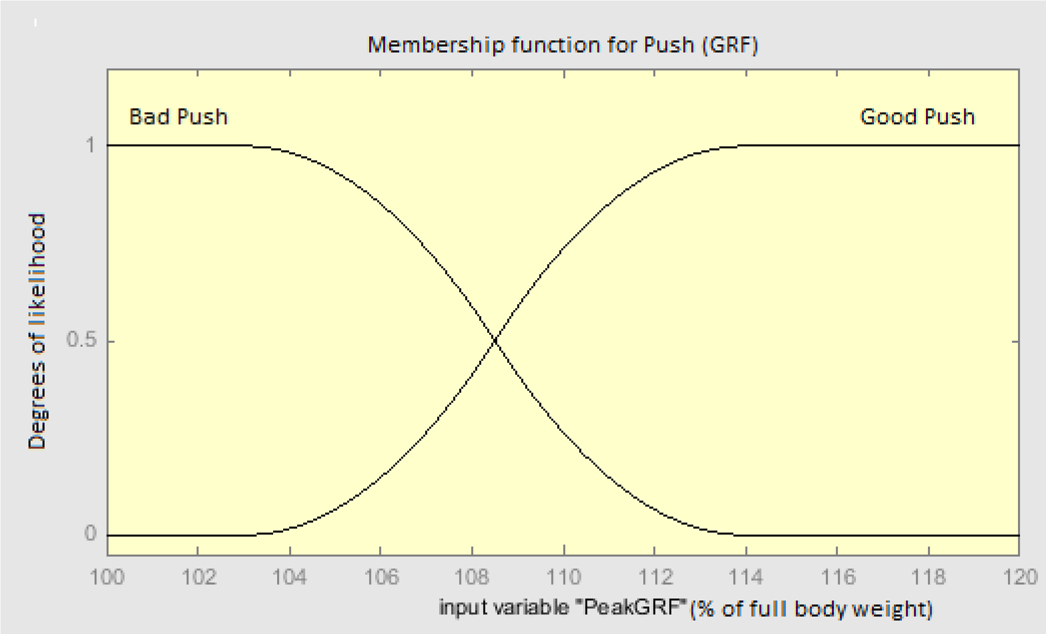


Figure 45: This figure shows the membership functions for mapping peak GRF to the degrees of likelihood of a good or bad push.

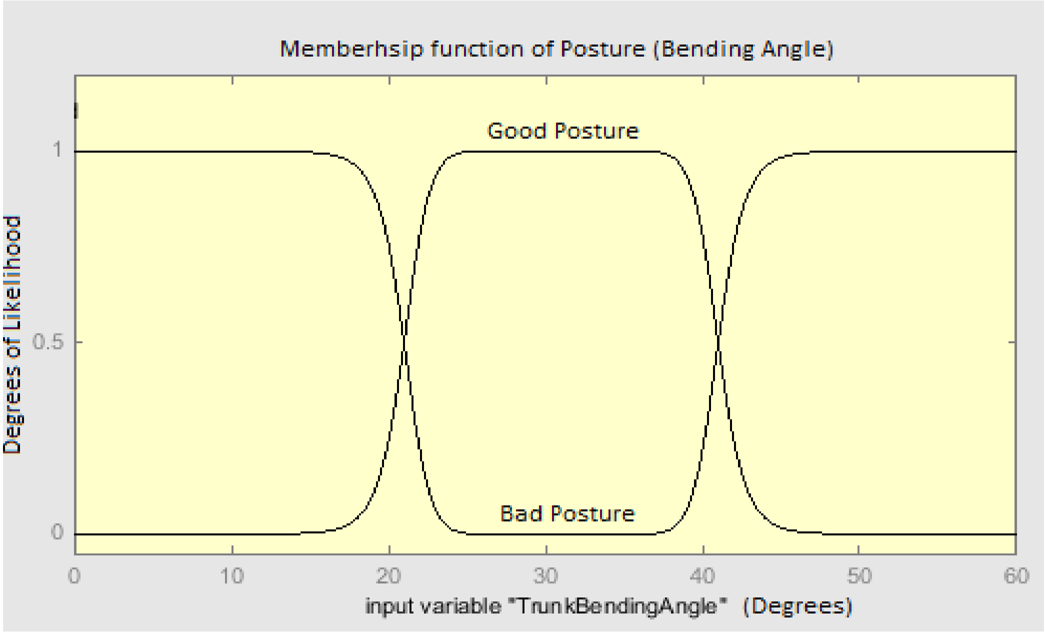


Figure 46: This figure shows the membership functions for mapping upper trunk bending (roll) angle to the degrees of likelihood of a good or bad upper-trunk posture when standing.

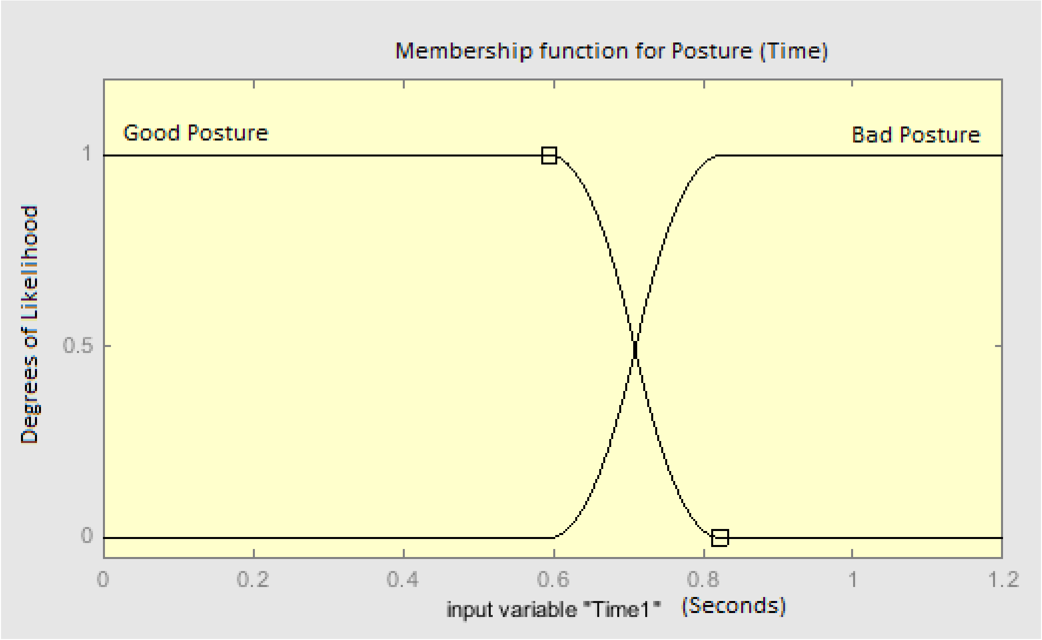


Figure 47 This figure shows the membership functions for time took for leaning forward to the degrees of likelihood of a good or bad upper-trunk posture when standing.

The shape of the membership functions was chosen as Gaussian. This is because from a statistical point of view, Gaussian membership function fits the human thinking process, which often characterises as a normal distribution (X. Liu, Zbou, & Power, 1999). The membership functions mapped all available crisp values from the inputs into DoL and each value belonged to one or two of the membership functions. The sum of DoL was within the range of 0 and 1. These fuzzy values were then used as a premise for decision-making by sets of fuzzy rules.

For instance, when the FIS interpreting DoL of a good impulse force (i.e. a push), once the peak GRF reached 103% of the full-body weight, the DoL of a good push starts to increase from 0. The maximum value of DoL is 1 and this is reached when the peak GRF hit 114% (as shown in figure 45).

5.3.3 Fuzzy Rules

The knowledge base consisted of logic rules. They are collections of "If-Then" statements describing the relationships between linguistic variables, which are the inputs, and outputs of the FIS. These logic rules were conditional expressions to link the premise and consequent fuzzy sets (Perfilieva & Lehmke, 2006) for the STS evaluation factors. Each of the "If-Then" statement has two parts, a premise part and a consequent part. The structure of the syntax as followed:

$$\boldsymbol{IF}\ a_1\ is\ B_1\ \square\ a_2\ is\ B_2\ \square\ \ldots\ \square\ a_k\ is\ B_k\ \boldsymbol{THEN}\ \ C$$

Where a is the DoL value of input a, B is a condition tested for a,
□ is a Zadeh operator (AND, OR, NOT), C is the consequent
given the premise values.

The FIS works out the consequent based on these rules. The DoL values of the inputs can be compared with other inputs by various Zadeh operators, AND or OR or NOT (Entemann, 2002). They deduce the value of the consequent. In fact, the AND operator will set the consequent to the minimum value of DoL based on the selected inputs while the OR operator will set the consequent to their maximum value instead. The NOT operator will calculate the consequent by taking away the current DoL value of the input from 1.

These rules determined the strength of the fuzzy outputs for each STS evaluation factor as shown in table 12. They were used to correlate the defined fuzzy propositions to a range of STS performance indications that based on the linguistic variables. The results of various rules were summed to generate a set of fuzzy outputs.

Table 12: Fuzzy logic rules adopted in interpreting STS performance functional factors.

Functional Factors	**Fuzzy Logic Rules**
Force-symmetry	IF (CoPx is good) AND (Lateral Bending (pitch) Angle is good) THEN (Force-symmetry Score is good) IF (CoPx is bad) AND (Lateral Bending (pitch) Angle is bad) THEN (Force-symmetry Score is bad)
Impulse for push when rising	IF (Peak GRF is good) AND (Peak Vertical Velocity is good) THEN (Push Score is good) IF (Peak GRF is bad) AND (Peak Vertical Velocity is bad) THEN (Push Score is bad)
Trunk forward lean angle	IF (Lean (Roll) Angle is good) AND (Lean Time is good) THEN (Lean Forward Score is good) IF (Lean (Roll) Angle is bad) AND (Lean Time is bad) THEN (Lean Forward Score is bad)

5.3.4 Defuzzification

Lastly, defuzzification was achieved to convert the fuzzy results, to output values, in this case, STS performance scores in each evaluation category. These scores were used to generate feedback to users. Similar to fuzzification, the fuzzy outputs are transposed to their original membership functions to crisp values (see figure 48).

For instance, when the upper trunk peak velocity reached 0.2 ms^{-1} and the peak GRF reached 102% of the full body weight during an STS execution, the push score started to increase from 0 to 100 (see figure 50).

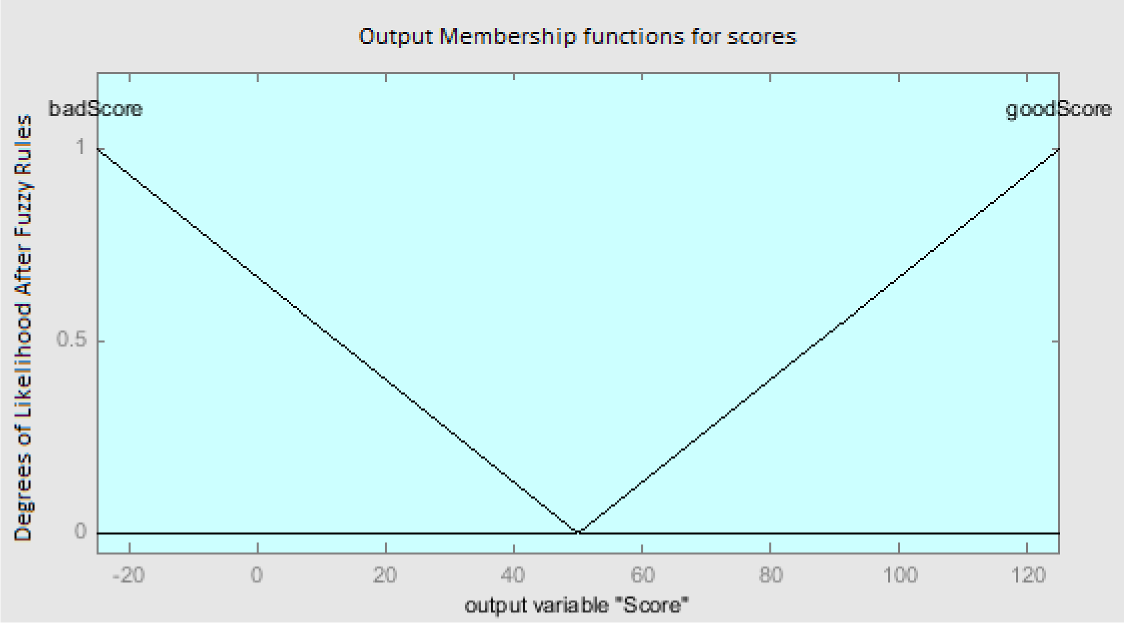


Figure 48: Figure is showing the membership functions for calculating the scores based on the output from the fuzzy system. The same functions were used to calculate all types of score.

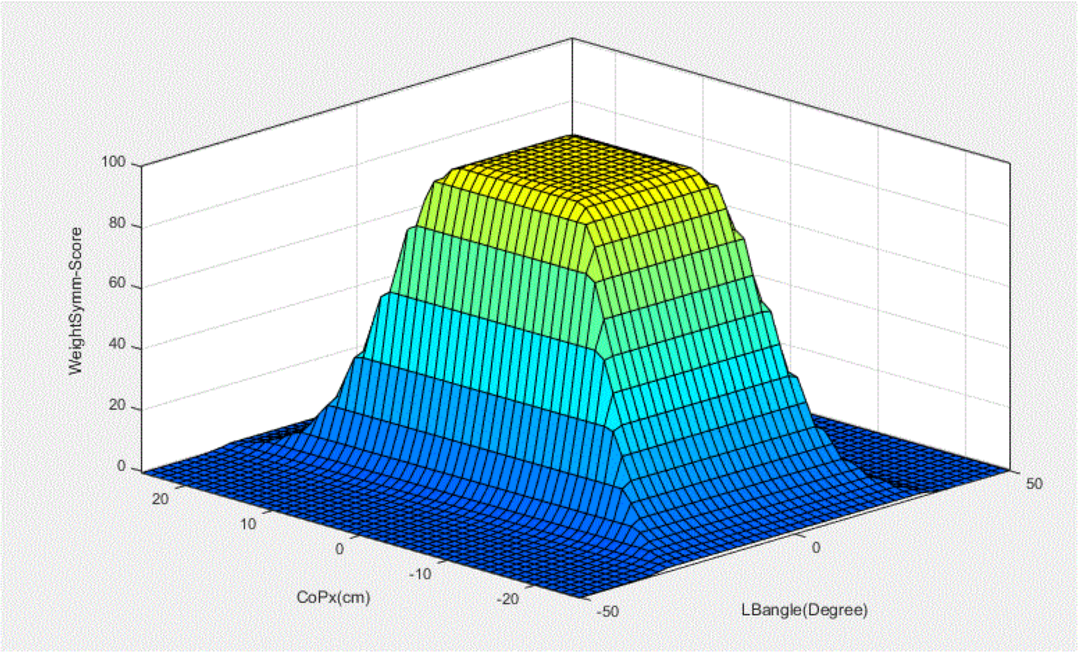


Figure 49. Input-output surface plot of the FIS: CoP (x) and upper trunk lateral bending (pitch) angle vs. force-symmetry score.

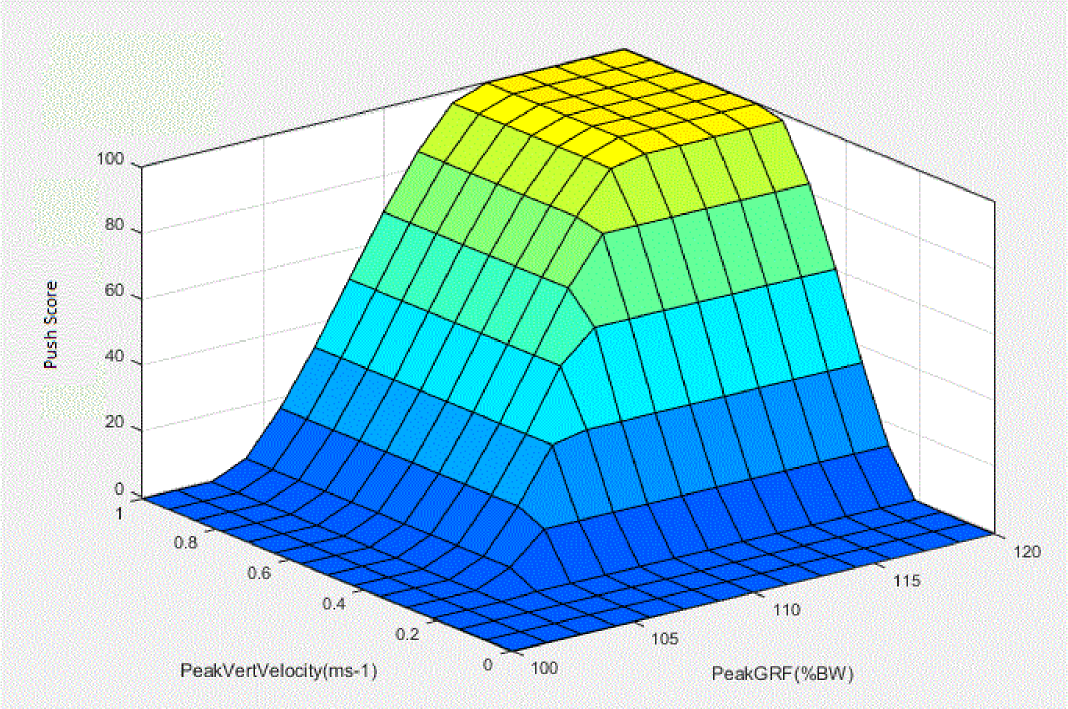


Figure 50: Input-output surface plot of the FIS: Peak Vertical Velocity (x) and Peak GRF vs. Push score.

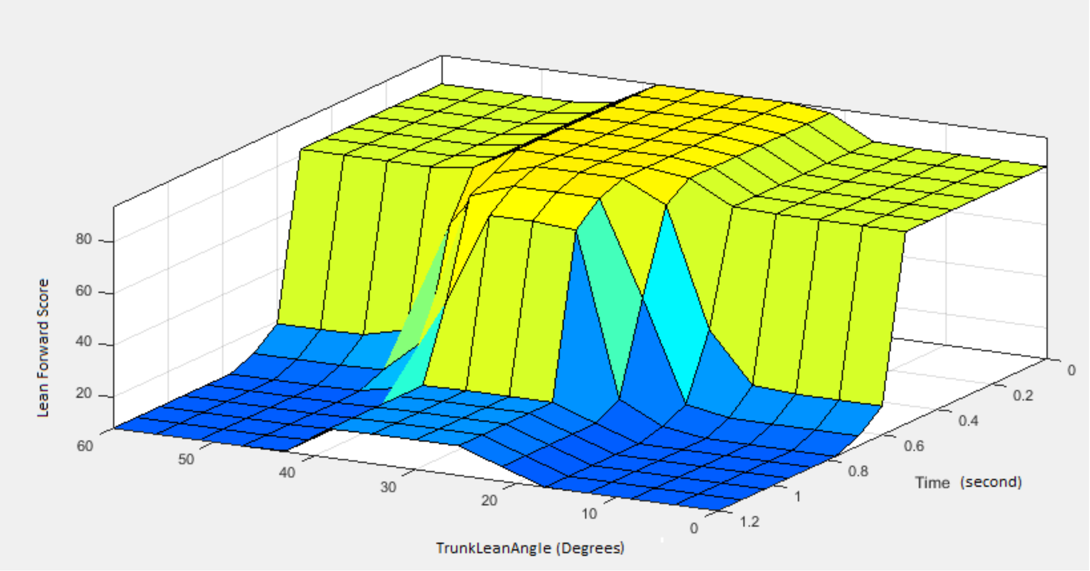


Figure 51: Input-output surface plot of the FIS: trunk lean (roll) angle and time for leaning vs. Lean Forward score.

5.3.5 Interpreting Scores to Feedback

Appropriate performance feedback was then generated in texts, in real-time and after training, based on the output scores for each of the three evaluation factors. This was because if only presenting a numerical score, there is a chance that users could misunderstand the feedback, however, explained feedback in words was considered to be more accessible to a broad range of people and is more understandable (see section 3.3).

While the user was practising the STS movement and when the force-symmetry score dropped below 50, knowledge of performance was then provided in real-time, for example, “please try to lean more to your right”.

If the user wasn’t leaning forward (as detected as the roll angle) to generate the momentum needed during the momentum-transfer phase, real-time feedback, “you need to lean a little further forward” was provided.

If the system detected an unsuccessful movement attempt based on the scores, specific feedback instructions were provided for subsequent attempts. For example, a lack of forwarding lean would prompt the real-time feedback, “try to move your head forward over your knees”.

When the user had successfully executed several STS movements at the end of the training session, conclusive feedback on their performance based on the scores (e.g. “you leaned a little too far to the right” or “try to push down harder next time”) as well as motivational feedback (“you are standing up very well”) were provided.

The automated feedback generation system was first modelled on Fuzzy Logic Toolbox (Matlab R2013a, MathWorks, Natick, Massachusetts, U.S.A.) to test the responses. Then, the system was implemented in the programming language, C. The written software was compiled on LabWindows/CVI (Version 2012, National Instrument, Austin, Texas, U.S.A) and ran on a control software suite (LabVIEW, Version 2013 SP1, National Instrument, Austin, Texas, U.S.A) for testing and evaluation.

5.4 Implementation of the Visual Feedback System

The performance feedback generated by the AFGS was then displayed on a purposely designed visual feedback system (VFS). This stimulated the inside of a motor bus (figure 52), a situation in which older people have found to be physically challenging in real-life (Barnsley et al., 2012) and supported by stakeholders (see section 3.3) as they reportedly feel physically unsafe, fear about falling and injury when travelling on public transport. This has discouraged them from travelling outdoors. The system presents an augmented physical appearance of an interior of a bus, sound effect that mimics the ambient noise and an indication of the real-time progress that allows the user rehearses standing up from a passenger seat and imitates getting on and off the "moving vehicle".

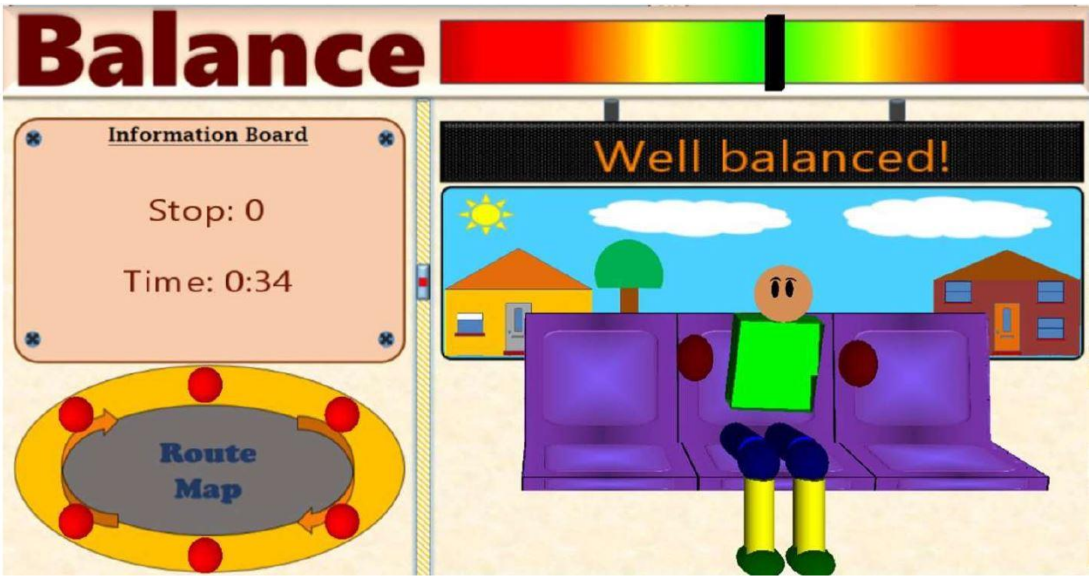


Figure 52: Showing the VR based visual feedback system (inside a motor bus) implemented in this study.

5.4.1 Multisensory Feedback

As soon as the training session starts, data are acquired from the sensor-fusion algorithm and the STS detection algorithm (see section 4.2). STS performance is then evaluated by the fuzzy-logic AFGS (see section 5.3). The outputs of the system then displayed on the VFS.

The VFS was employed throughout the training session to display the generated feedback on STS performance and encourage participation, repetition, without the presence of a therapist. The extrinsic feedback was delivered in two ways, visually and auditory. The real-time feedback was generated by analysing user performance throughout training and conclusive feedback is delivered when the training session ends. Their purpose was to offer guidance during and after practices, which is critical to motor relearning (Stanton et al., 2015).

The VFS system was created on a control software suite (LabVIEW, Version 2013 SP1, National Instrument, Austin, Texas, U.S.A) using various graphical and sound components.

5.4.2 Avatar

Real-time modulation (Roosink et al., 2015) was adopted to map the real-time kinematic data (i.e. upper trunk angles and vertical displacement) onto the avatar. Therefore, when the user moved, the avatar was “moving” with them.

The provided visual feedback allowed users to observe and acknowledge their real-time body movements as an interactive avatar on a computer screen. This mimicked mirror therapy, which patients practised with a therapist in front of a mirror while watching the reflection for visual feedback. Studies show this type of interventions can improve the effectiveness of motor relearning (Hung et al., 2015) (J.-Y. Park, Chang, Kim, & Kim, 2015).

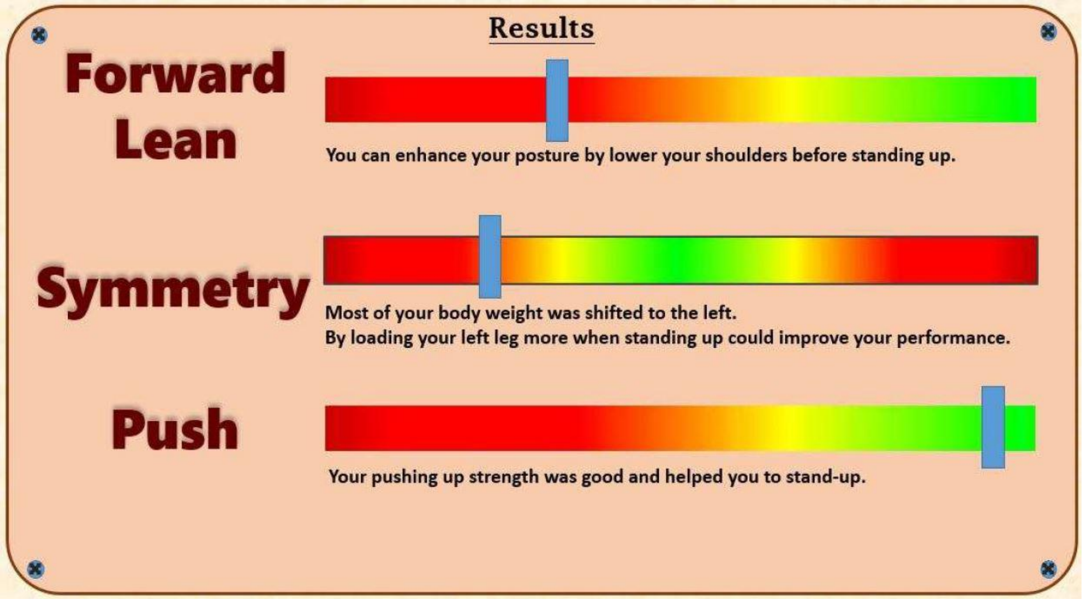
5.4.3 Real-Time Feedback

A meter bar, scaled from red to green, was implemented on the top of the screen with a pointer that moved sideways to indicate real-time force-symmetry. Auditory feedback for correcting user movement is provided when different stages of the STS movement was reached, and transcribed texts are printed on a "passenger message panel", in order to offer disability support for users with visual or hearing impairments. The texts were generated by the AFGS as discussed in section 5.3.5.

Along with knowledge of performance, which was mentioned previously in section 2.6.1, knowledge of results was also delivered on an "information board" (see figure 52). This included the total playing time and the number of successful STS executions, which was presented as a number of bus stops completed. A "route map display" is implemented and positioned below the board. The map shows a bus route consists of six stops, each is represented by a “blinking light” and turned from red to green in clockwise when an STS movement was successfully executed. Users were able to see their improvement with a defined goal of movement repetition which aimed to increase motivation. This automated technology allowed users to self-practice and advise on improvement without the presence of a therapist.

5.4.4 Conclusive Feedback

At the end of the training, conclusive feedback was provided on the three main characteristics of the movement (See figure 53). Furthermore, the system recorded users’ achievements for each session and maintained a set of data files that could be analysed by therapists including, playing time, the number of successful STS executions, performance scores and performance of different kinematic metrics (e.g. maximum vertical velocity, angles and GRF). This data could then be used by therapists in formulating treatment plans as well as evaluation of therapy. This could simplify performance tracking and monitoring of performance.



Results

Forward Lean

You can enhance your posture by lower your shoulders before standing up.

Symmetry

Most of your body weight was shifted to the left.
By loading your left leg more when standing up could improve your performance.

Push

Your pushing up strength was good and helped you to stand-up.

Figure 53: Showing the conclusive feedback provided by the visual feedback system to users.

5.5 <u>Feasibility Study</u>

In order to test the acceptability and feasibility of the system for self-management, clinical adoption and possible home-management as well, mobility-impaired older adults (n = 5) were invited to attend a feasibility study session. Firstly, the researcher explained the purpose, procedure and activities to be conducted during the session. Instructions for controlling the VFS (i.e. to start/stop the program) were clarified with a demonstration before full written consent was sought. A five-minute interview was then conducted before the test to gather some background information including, age, gender and self-reported STS abnormalities based on the feedback from their therapists. The Montreal Cognitive Assessment (MoCA) was used to assess participants' cognitive ability at the time of testing (appendix 6). The researcher then made measurements (height and weight) to characterise the participants.

Once these were achieved, the participant sat on a standard chair (seat height 49.5 cm) with armrests. The participant then wore a vest which contained an inertial sensor located in a pouch on the vest. The lightweight vest provides comfort for the chest and shoulder areas but it was tightly tied around the waist where the inertial sensor was placed. This was to prevent inaccuracy due to movements of the loose vest.

The sensor was connected to the laptop via a USB cable while the participant's feet were positioned on the force plate. The participant was asked to start the VFS using a mouse. After that, the participant practised the STS movement and repeated the movement six times at their own comfortable pace.

Throughout the testing session, each participant was able to observe their movements as an avatar on a computer screen generated by the VFS along with feedback messages delivered by the AFGS. Once this was completed, the participant was then asked to remain seated on the chair and rest for as long as needed. After the resting period, the participant repeated the practice for a maximum of five minutes until the end of the study session, which lasted for 30 minutes. At the end of the session, opinions of the overall system were asked for and noted by the researcher.

5.5.1 Feasibility Study Results

The same participants who took part in the trial discussed in section 4.2.3, participated in this testing session again. All participants received over 26 points in the repeated MoCA, which suggested their cognitive and mental ability was normal (Nasreddine et al., 2005). They communicated their opinions about the system via a semi-structured interview at the end of the session.

Before the participants practised on the system, the researcher questioned their experience of rehabilitation particularly in regarding the relearning of the STS movement. All participants emphasised the limited access to rehabilitation services after being discharged as they received restricted rehabilitation therapy after transferred home, notwithstanding that they wanted to improve their physical ability and return to a normal life. Four participants reported that they received only one to three hours of support per week with a therapist for several weeks, another participant suggested that she had never received any support at all after discharged. They suggested a technology-based feedback system would be helpful to their recovery.

None of the participants had experienced using computerised rehabilitation systems but had some experience in using systems at home, such as the Wii Play (Nintendo, Kyoto, Japan) and various phone apps. The idea of providing automated feedback on performance without the presence of a therapist was warmly welcomed. The concept of using automated technology (i.e. inertial sensor and force plate) to capture real-time biomechanical motion data was praised by the participants as they might be used “anywhere”. One of the participants was surprised with the low-cost nature of the technology and suggested that “she will definitely be buying the system at this price” while condemning the lack of support from the government health service, “NHS (National Health Service) offers free drug prescriptions but not something like “this” (technology rehabilitation). You know, it can be shared among my members (i.e. Glasgow Chest, Heart, Stroke Scotland Club), and lasts for years.”

The feasibility of the system for self-use was evaluated in the test sessions. All participants had no problem of following the provided instructions from the researcher to start or terminate the VFS using a mouse. Regarding the ease of use, all participant found the system to be user-friendly. This could be due to the fact that all interactions with the computer was minimised when starting the training program and to the existence of visual and verbal instructions and feedback provided in real-time and at the end of training.

All participants required the use of armrests when standing. Most subjects were capable of putting the vest on and off and tying the vest on their own. A participant suggested that “this apron is a very good idea”, however, one participant found it rather difficult to tie the knots as they were not long enough.

Two participants had trouble placing the inertial sensor in the small pocket suited on the vest as they were unable to put a USB cable and plug through a small hole underneath the vest.

5.5.2 Visual and Auditory Feedback

All participants revealed that they had no problem in understanding the system instructions and the generated verbal and visual feedback. This also confirmed the researcher's observations of participants quickly navigating through the processes and apparent happiness to wait the 15 seconds for the software to load.

Regarding the VR environment, participants realised the VR would be beneficial for geriatric patients as it was not as "boring" as manual standard practices and visually "beautiful to look at". A participant said, "it will be very useful for her and her club members" and predicted that "they will love it". The amount of movement feedback provided in real-time was reasonable according to the participants who could read the numbers and messages while standing up. When the researcher was explaining the introduction of more animations (moving passengers and moving objects outside the "window") to a participant, she was shaking her head and recommended that "this would be too much" and "they could become a distraction". The participant thought "this is enough for me" and believed "others will agree".

The real-time and conclusive feedback provided by AGFS for the functional evaluation of the STS movement in mobility-impaired older adults, all matched the self-reported STS abnormalities provided by the participants. They were happy and enjoyed the idea of providing mirror feedback through the avatar. A participant was giggling and stated that “this was the first time I could see my body when I am standing up”. Some concerns were raised regarding the textual feedback (i.e. conclusive feedback) as they were too small, and three participants were unable to read the text without a pair of reading glasses. Continuing STS executions for three times in a row caused one participant, who had arthritis, to complain about their knees and back pain and refused to stand before rested for about five minutes. The participants indicated the textual visual interface may not be suitable for patients with aphasia or cognitive issues.

5.6 Discussion

The aim of this part of the project was to present a new feedback training system for regaining the STS movement in geriatric rehabilitation. This comprises the adoption of an AFGS to analyse movements and generate performance information for the delivery of feedback in real-time and at the end of training.

In this chapter, responses from mobility-impaired older adults considered the VFS as positive. The user feedback showed the system to have a potentially high acceptability for use in homes or in a clinical environment. However, the general usability and usefulness of the feedback platform could be improved in further studies by including variables that could give more details about the movement of joints and muscle activations of different body segments. However, this would likely to increase the system complexity (e.g. more sensors) and cost.

Although the visual feedback was accepted by all participants, suggestions showed it could pose a difficulty for users with aphasia or cognitive issues when reading text or listening to auditory feedback. As discussed in chapter 2, there were research studies working on producing automated feedback on the STS performance, however, their methods of delivering performance information are inadequate for self-use in rehabilitation. These issues were avoided in this study as it has first engaged the stakeholders throughout its design to remove key barriers of translating technologies into homes and clinical environment as discussed in chapter 3.

This study is one of the very first in the fields to investigate the use of real-life VR technology in training the STS movement. This has a potential to increase patient’s motivation, time spend in training, effort into promoting recuperating compared to standard physical interventions as demonstrated in other VR systems for training various movements (Kim, Yoo, & Im, 1999) (Broeren et al., 2004) (Cardoso et al., 2006) (Liebermann et al., 2006) (Gavish, Gutierrez, Webel, & Rodriguez, 2011). The findings from the feasibility study also showed the older adults enjoyed practising with the VR system and suggested it could be a supplement to clinical rehabilitation and further enhance motor relearning experience and potentially, the rate of recovery.

Based on the feedback and opinions from users, the conclusive feedback and the size of texts shall be re-edited to suit geriatric patients with visual impairments such as the use of simpler terms and enlarged fonts. The force plate was found to slip away from users, this could potentially be a safety issue. The metallic legs supporting the force plate were found to be the cause of the issue. After putting adhesive heavy duty anti-slip tape (Safety-Walk, 3M, Minnesota, US) on each of the leg, the issue was resolved.

The fuzzy controller and the visual feedback systems were developed from the findings of the conceptual design stage (i.e. real-time feedback presentation, conclusive feedback presentation and portable wearable technology) of the user-centred design (See section 3.2.3.2).

The design of the systems addressed the design criteria as details in section 3.3 by providing adaptability to suit a range of physical abilities and body dimensions. According to all participants' feedback, the system has a user-friendly, interactable and consistent interface that provides a positive training experience.

The participants welcomed the detailed design of the system. The developed system was based on the engineering concepts selected by stakeholders as explained in section 3.2.3.2. The concept of providing real-time feedback was slightly modified as a “message board” was introduced to provide textual instructions and feedback on real-time STS performance. The findings from this chapter informed the detailed design stage of the total design framework as design criteria, such as the size of text-based feedback, number of repetitions and training time, were all refined following feedback from participants were obtained. The positive response received during the feasibility stage has also confirmed the conceptual design as stated in section 3.2.2.2. However, the detailed design of the system should be tested in a clinical environment to confirm its feasibility and effectiveness as part of the total design framework. The effectiveness of the system was tested in a randomised control trial in a clinical environment as explained in Chapter 6.

5.7 Summary

A feedback platform for providing STS performance feedback to geriatric patients was developed. The platform has two components, an AGFS and a VFS. The AGFS is based on a fuzzy inference system, which was aiming to provide feedback on force-symmetry, impulse force during rising and trunk forward lean which is usually provided by therapists in rehabilitation. The VFS was based in a VR environment mimicking a motor bus. User body movements were mirrored as an interactive avatar and feedback on STS performance was provided visually (i.e. bar charts and texts) and auditory.

A testing session was conducted. Five mobility-impaired older adults practised the STS movement using the feedback system, which was broadly welcomed by the participants. The performance feedback generated by the system matched the self-reported STS abnormalities. The participants found the visual feedback was engaging and potentially helpful for other mobility-impaired older adults, such as geriatric patients.

Chapter 6. Feasibility Study: A Randomised Controlled Trial

6.1 Introduction

In the previous chapter, it was shown that older people with impaired-mobility found the visual feedback system (VFS) to be motivating and engaging compared to standard physiotherapy, with suggested positive effects on rehabilitation outcomes. A clinical evaluation of the system was considered to be the next step in demonstrating the system's utility as a rehabilitation technology in a clinical setting. Before recommending such a system for use in clinical practice, it was important to determine the evidence regarding its feasibility and effectiveness.

This chapter describes the methods and results of a randomised controlled trial (RCT) exploring the clinical acceptability and feasibility of the system described in the earlier chapters. The trial also aimed to gather data on the effectiveness of the system compared to standard rehabilitation in training the STS movement. The study protocol was shaped through discussion with the clinical team (a senior physiotherapist and a medical consultant) and published literature in this area (Fung et al., 2012) (Klamroth-Marganska et al., 2014) (van den Berg et al., 2016) (Weathers et al., 2016).

6.2 Primary and Secondary Aims

In the context of product development processes, the term "feasibility study" is defined as "evaluating whether an idea is realisable under certain circumstances" (Bause, Radimersky, Iwanicki, & Albers, 2014). Clinical evaluations of the feasibility of new medical technologies are essentials as they generate evidence to determine whether new devices have the potential to address unmet clinical needs and improve therapy outcomes. Responsible healthcare providers would only consider adopting technologies if compelling evidence demonstrated they are not only effective but also practical within a clinical environment (Holmes et al., 2016) as discussed in section 3.3.

Therefore, the primary aims of this study were to examine the acceptability and feasibility of the overall feedback system for training the STS movement in a clinical environment. Factors that could interfere with the clinical adoption of the system were explored. This included the feasibility of its interventions, practicability and performance measurements produced by the system. Feasibility focuses on three metrics:

1. Recruitment to the study as a proportion of individuals meeting the criteria and approached to participant,
2. Adherence to the training schedule (i.e. the proportion of training sessions participated in to the number of sessions offered),
3. The number of STS repetitions achieved as a percentage of the set goals.

Acceptability was assessed from participants and healthcare professionals' feedback on a range of design and practical issues, such as set-up time, portability and space required so that the system’s suitability to the clinical environment could be assessed.

The hypothesis for this primary aim was that the system would be considered feasible to use within a health service rehabilitation environment and that it would be acceptable as a training system by health professionals and individuals receiving rehabilitation.

The secondary aim was to gather preliminary evidence on the system effectiveness for improving STS performance. The hypothesis formed for this aim was that “participants who trained with the feedback system would show greater improvement in their STS performance (using the five times sit-to-stand test (FTSTST)) and STS behaviour (using daily STS movement counts) than participants who only receive standard rehabilitation during their stay at the hospital”.

6.3 Study Design

6.3.1 Clinical Setting

The clinical trial, including recruitment, training and data collection, took place in a geriatric rehabilitation unit at Gartnavel General Hospital, Glasgow, Scotland, U.K.. The unit provides physical rehabilitation for older people who are currently unable to live independently. Most of the patients are transferred from orthopaedic and general medicine units from across Glasgow. Their original reasons for admission ranging from fractured hips to neurological disorders, such as Parkinson’s diseases and stroke.

6.3.2 Recruiting Criteria

A set of inclusion and exclusion criteria for recruiting appropriate participants was created through discussion with the clinical team and published literature in geriatric rehabilitation.

Inclusion Criteria

1. Patients admitted to the geriatric rehabilitation unit at Gartnavel General Hospital,
2. Patients with physical impairments that affect their ability to stand up from sitting as determined by an NHS physiotherapist,
3. Patients that are medically stable as determined by a geriatrician,
4. Patients able to give informed consent,
5. Patients able to complete at least one STS movement with/without the help of a mobility aid or assistance of one other person,
6. Patients able to follow three-word instructions in English.

Exclusion Criteria

1. Patients unable to read feedback on a computer screen with or without the use of visual aids,

2. Patients who are known to be epileptic/photosensitive or experience blackouts when exposed to certain light patterns or flashing images,
3. Patients with coexisting physical impairments which prevent the practice of STS e.g. bilateral amputee or an acute exacerbation of rheumatoid arthritis,
4. Patients not expected to survive the study period,
5. Patients with active dermatological problems that may preclude the use of double-sided sticky tape,
6. Patients with active medical conditions that may limit prescribed mobility exercises e.g. unstable angina.

6.3.3 Ethics

These policies were passed by the NHS West of Scotland Research Ethics Service (West of Scotland REC 05, reference: 16/WS/0250) and the University of Strathclyde's University Ethics Committee (UEC 16/69). The clinical team, consisting of a consulting geriatrician, senior physiotherapists, physiotherapists, occupational therapists and physiotherapy support workers were responsible for identifying potential participants using the criteria stated in section 6.3.2.

The trial was registered with the National Institutes of Health (US National Library of Medicine), ClinicalTrials.gov Identifier: NCT02925039. The Results and study termination forms have been submitted (10/09/2018) but not reviewed or approved by the protocol registration and results system (PRS).

6.3.4 Sample Size

An appropriate sample size to answer this study’s null hypothesis was calculated based on a power calculation. The significance level was set at 0.05 following a widely used statistical convention (Jones, 2003). The study power was determined as 85% given the feasibility of this study with a small population. The effect size (improvement in daily STS executions) was set at 14% and the standard deviation was set at 3.5. These estimations were obtained from a successful RCT in testing functional strength training to improve STS recovery in the older population for six weeks (A. Kerr, Clark, Cooke, Rowe, & Pomeroy, 2017).

The results suggested 36 participants in total, 18 in each group, were needed for the calculated statistical power of 85%. The attrition rate of clinical trials on older adults was reported around 15% (Cherubini, 2015). Therefore, the aim was to recruit 40 participants in total.

6.3.5 Recruitment Process

Potential participants with physical impairments that affect their capacity to perform the STS movement and about to start physical rehabilitation were identified by the clinical team on the ward. A member of the clinical team then approached the individual providing a summary of the clinical trial to gauge interest. If the identified individuals indicated interest in participating, a mutually convenient time was arranged for the researcher to speak to them about the study. If the individual was still interested, an information sheet (see appendix 1) was left with the patient and they were encouraged to read this and speak to family and friends about their possible participation.

No less than 48 hours after the information sheet was provided, the researcher contacted the potential participant again to discuss their participation and receive their written consent, if agreeable. This was to ensure all participants had sufficient time to consider joining the study. This recruitment process and participation in the study did not interfere with ongoing discharge planning.

6.3.6 Randomisation

Block randomisation in blocks of four to ensure balanced groups (Efird, 2011). The randomisation order was predetermined with the group allocation placed in opaque envelopes which were opened by the researcher after the baseline measures had been taken.

6.3.7 Demographic and Clinical Data

The collected information contained key factors which could affect clinical outcomes. Age, which is well-documented as the main reason for the decline in mobility (Rantanen, 2013). Since women have a reported poorer physical performance than men, based on their activities of daily living (Zunzunegui et al., 2015), gender was also considered to be an explanatory factor. The presence of co-morbidities may also be a factor in a poorer outcome from rehabilitation, consequently, the number of co-morbidities was recorded. Height and weight were recorded to help generally characterise the recruited sample.

Table 13: Details of demographic and clinical data recorded.

Demographic Information	**Clinical Information**
Age Gender Height Weight	Date of Admission Reason for Admission Comorbidity

6.3.8 Baseline Measurements

Given the specific nature of the training intervention, focusing on the STS movement, a baseline measure of STS performance was considered essential. The five-times sit-to-stand test (FTSTST) was introduced as a standardised measure of lower limbs strength (Csuka & McCarty, 1985). The original testing procedure involves the participants stand-up from a sitting position five times continuously as quickly as possible with the time taken to achieve five complete executions recorded as the result, longer durations indicating poorer performance. This test has been shown to have a strong correlation with balance disorders (Bohannon, 1998) (Lusardi, Pellecchia, & Schulman, 2003) (Duncan, Leddy, & Earhart, 2011), general mobility (Goldberg, 2012) and cognitive conditions (Duncan et al., 2011) (Annweiler et al., 2011). Studies have demonstrated the results obtained from the test can also predict incapacity (Guralnik, Ferrucci, Simonsick, Salive, & Wallace, 1995) and risk of falls (Jordre, Schweinle, Beacom, Graphenteen, & Ladwig, 2013) (Doheny et al., 2013). Therefore, it was adopted in this trial as a baseline measurement.

6.3.9 Clinical Measures of General Mobility

Any changes in the STS performance is likely to impact on general mobility, therefore, commonly used clinical measures of mobility were incorporated into the baseline measures. The following assessments were chosen for their acceptable levels of validity and reliability and because they were recorded routinely at the clinical site.

6.3.10.1 Tinetti Assessment Tool

The Tinetti Assessment Tool (TAT) (Tinetti, Franklin Williams, & Mayewski, 1986) is a 28-point task performance exam in which clinicians score performance on a range of functional tasks from 0 (total impairment) to 2 (fully independent), such as rising from a chair, standing balance and stepping symmetry (see appendix 6). The tool has been validated to assess physical functions in older adults (Raîche et al., 2000) (Zimbelman et al., 2012) (Kloos, Fritz, Kostyk, Young, & Kegelmeyer, 2014).

6.3.10.2 Elderly Mobility Scale

The Elderly Mobility Scale (EMS) (Smith, 1994) was specifically designed for screening dependency with activities of daily living (ADLs) in older adults (De Morton & Nolan, 2011). Participants conduct functional tasks, such as transferring from a lying position to a sitting position, walking for 6 meters and standing still. Each task is ranked from 0 (dependent) to 3 (fully independent) (see appendix 6). A score of 14 and over means the participant is capable of conducting ADL tasks independently, while a score of 10 and under means the participant requires help with basic daily tasks such as dressing and toileting.

6.3.10.3 Activity Data

An ActivPAL physical activity monitor (PAL Technologies, Glasgow, Scotland, U.K.) was attached to each participant's dominant side of thigh for the 48 hours following consent, right before the start of the training program.

Figure 54: Showing an ActivPAL sensor placed on the anterior thigh with Tegaderm (3M, Maplewood, Minnesota, U.S.A.).

This small (53mm x 35mm x 7mm) and lightweight (18 gram) accelerometer-based sensor has been used in clinical research (Montoye, Pivarnik, Mudd, Biswas, & Pfeiffer, 2017) and established validity and reliability (Edwardson et al., 2017). The sensor was located on the anterior thigh according to manufacturer instructions and held in place with Tegaderm (3M, Maplewood, Minnesota, U.S.A.) to minimise the risk of skin irritation and waterproof the sensor (see figure 54).

In this trial, the sensor was used to gather the number of daily STS executions and step counts from each individual participant 48 hours before and after the training interventions in understanding their level of activities.

6.3.10 Outcome Measurements

Within 24 hours of completing the trial, the FTSTS test, TAT and EMS were conducted again to measure mobility performance. An ActivPAL sensor was then attached to participants' dominant side of thigh.

6.4 Results

6.4.1 Recruitment

Recruitment commenced on the 18th of April, 2017 and ended on the 22nd of September, 2017. During that period, a total of 26 potential participants (n = 26) were identified by the clinical team in which 18 met the criteria (n = 6 excluded due to cognitive impairments and n = 1 due to blindness) and one patient declined to participate. 18 participants (n = 18) consented to join the trial and 16 participants (n = 16) completed the trial meaning there was a conversion rate of 89%. All participants were successfully randomised to either the experimental group (n = 9) or the control group (n = 9), see figure 55 for an outline of the recruitment and allocation.

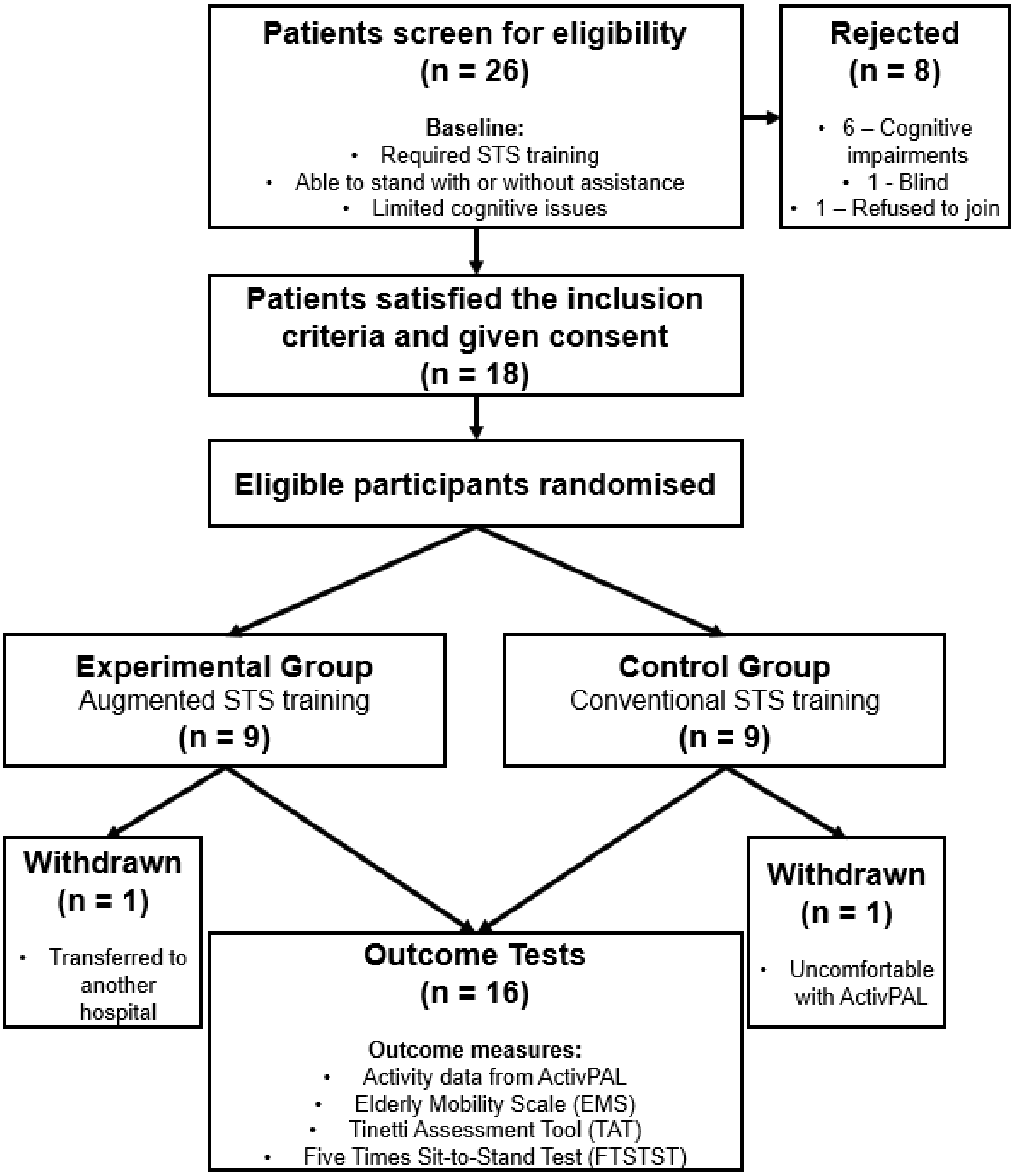


Figure 55: An outline of the recruitment and allocation.

Table 14: Participants' baseline characteristics recorded pre-trial. Mean (S.D.).

	Experimental Group	**Control Group**	**p-value**
Age, Years	80.75 (7.81)	81.74 (6.88)	0.345 (not statistically significant)
Gender (Males / Females)	2/6	2/6	N/A
Reason for admission	Hip fracture: n = 4, Hip and shoulder fracture: n = 1, Neuropathy pain in lower limbs: n = 1, Stroke: n = 2.	Hip fracture: n = 2, Shoulder fracture: n = 1, Ankle fracture: n = 1, Osteomyelitis: n = 1, Leg amputation: n = 1, Parkinson's n = 1, Pain in hip: n = 1.	
TAT Point	8.75 (3.92)	9.38 (5.55)	0.80 (not statistically significant)
EMS Score	2.75 (2.12)	5.00 (3.42)	0.14 (not statistically significant)
Fully completed FTSTST	0 participant	1 participant	N/A

6.4.2 Retention

16 participants maintained in the study until discharged. A participant withdrew from the experimental group as they were transferred to another hospital a day after consent and a control group participant refused to continue as they were uncomfortable with wearing an ActivPAL sensor.

6.4.3 Feasibility of the System

6.4.3.1 Training System Set-up

The initial setup (see figure 56) consisting of a mini-desktop (Elitedesk 800, Hewlett-Packard, Palo Alto, California, U.S.A.), a projector (W2000, BenQ, Taipei, Taiwan), force plate (50:50, Bertec Inc, Columbus, Ohio) and an inertial sensor (PhidgetSpatial 3/3/3, Phidgets Inc, Calgary, Alberta, Canada) was initially located in a therapy room, a short distance from the ward. Initially considered by the clinical team to be the most pragmatic solution, it quickly became apparent that this setup created unforeseen logistical problems. In particular, transporting participants from the ward to the training area placed additional physical demands on the participants and reduced the time available for training. On discussion with the clinical team, this set up was considered sub-optimal. An alternative solution replacing the mini-desktop and projector with a large screen laptop (Tecra R950, Toshiba, Tokyo, Japan) allowed the training to take place next to the participant’s bed on the ward. This was considered to be a more efficient set up. Only the first training session was conducted in the training area. Due to practicalities getting participants to the training area, all subsequent training was delivered next to the participant's bed.

Figure 56. A photo shows the initial setup in a therapy room.

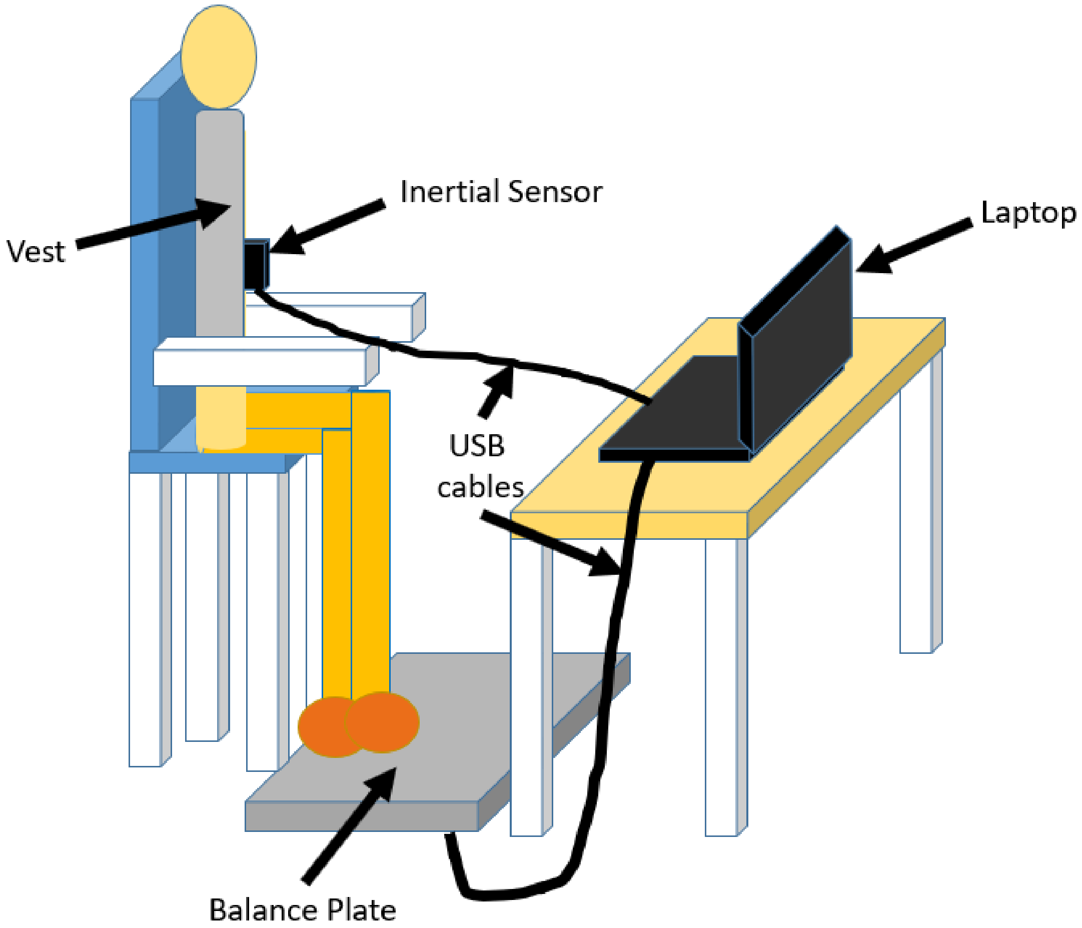


Figure 57: System set-up for the RCT.

6.4.3.2 System Compliance

The system compliance rate was 100%. All experimental group participants and clinical staff complied with all the training sessions. Due to relocation to another hospital, one experimental group participant withdrew after consent was provided but before their first training session.

6.4.3.3 System Adverse and Serious Adverse Events

There were no adverse events nor serious adverse events reported during the course of the study.

6.4.3.4 Training Frequency and STS Executions

The following tables (table 15 and 16) show the numbers of successful STS executions with or without assistance achieved by the participants in both groups during each training session. The figures recorded in the experimental group based on the researcher’s observations while the numbers in the control group were noted by their therapists on medical notes.

Table 15: Number of STS movements executed by participants in the experimental group in each training session.

	Experimental Group													
	Week 1			Week 2			Week 3			Week4			Average STS per session	SD
Participant	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3		
E1	3	3	3	7	3	3	12	-	-	-	-	-	4.86	3.48
E2	2	3	6	6	12	12	-	-	-	-	-	-	6.83	4.31
E3	2	4	6	-	-	-	-	-	-	-	-	-	4	2
E4	4	4	6	-	-	-	-	-	-	-	-	-	4.67	1.15
E5	3	6	4	6	6	8	10	15	16	8	12	3	8.08	4.38
E6	3	5	7	6	6	6	6	-	-	-	-	-	5.57	1.27
E7	4	6	3	7	8	6	-	-	-	-	-	-	5.67	1.86
E8	6	6	11	6	6	8	6	-	-	-	-	-	7	1.91
E9	N/A	-	-	-	-	-	-	-	-	-	-	-	N/A	N/A
												Mean	5.84	2.55

Table 16: Number of STS movements executed by participants in the control group in each training session.

	Control Group													
	Week 1			Week 2			Week 3			Week4			Average STS per session	SD
Participant	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3		
C1	N/A	-	-	-	-	-	-	-	-	-	-	-	N/A	N/A
C2	4	6	-	-	-	-	-	-	-	-	-	-	5	1.41
C3	4	10	-	-	-	-	-	-	-	-	-	-	7	4.24
C4	4	3	5	3	4	-	-	-	-	-	-	-	3.8	0.84
C5	8	5	6	6	6	6	5	-	-	-	-	-	6	1
C6	1	2	3	3	6	6	6	6	-	-	-	-	4.13	2.1
C7	1	1	2	4	3	3	3	-	-	-	-	-	2.43	1.13
C8	10	-	-	-	-	-	-	-	-	-	-	-	N/A	N/A
C9	5	0	0	5	2	3	3	3	3	-	-	-	2.67	1.80
												Mean	4.43	1.79

Participants in the experimental group performed an average of 5.84 (2.55) STS movements per session, while the control group performed an average of 4.43 (1.79) STS transfers per session.

6.4.4 Acceptability

To assess the system's acceptability, each participant was interviewed after the trial and any informal feedback offered during training sessions was recorded. The following section details the results of the interviews and user feedback obtained during the sessions. A thematic theory approach (Fereday & Muir-Cochrane, 2006) was adopted for the analysis of all these data. The results are therefore grouped into four identified themes which reflect the themes identified in the user-centred study in chapter 3.

6.4.4.1 Feedback from Users

Theme 1: Motivation

The auditory feedback delivered by the system provided encouragement to participants. When the term "Well Done!" repeated visually and verbally at the end of each successful STS execution, participants reacted positively. Six participants provided informal and non-verbal signs that they were enjoying the interactions with the system. One participant suggested computerised feedback messages were more believable than generated by healthcare professionals.

E8 (Experimental group, participant 8): **"I feel this (pointing at the feedback system) gave me something very different compared to the girls (physiotherapists). They keep telling me I am doing very well, but you**

know, it is just part of their job. I am sure computers will say I do well only if I really did it".

The conclusive feedback motivated several participants to practice more. Participants E1, E2, E5, E7 and E8 asked to repeat the augmented training after they read the feedback at the end of training and hoping to achieve a much better performance based on the provided information.

E1: **"Let's try again, shall we?"**

E2: **"No, I want to try again. Do it now."**

E5: **"I thought I did good."** Participant asked whether the researcher and the support worker had the time to repeat the training, **"Do you have any other patients to see now? Can I do it again?"**

E7: Participant frustrated with the conclusive feedback that was shown. They said, **"there is nothing I could do about it"** while shaking their head sideways and requested a new training session.

Theme 2: Automated instructions and performance feedback

From the start till the end of training sessions, all participants listened and paid attention to the automated instructions (i.e. "Go! Please stand-up when you can!") provided to initiate the movement. When they struggled to stand, they followed the feedback generated by the automated feedback generation system (i.e. "Move your head over knees", "Too far forward", "Push up", "Straighten up") to complete the movement.

Several participants mentioned that the instructions provided had helped them execute a successful STS movement. However, additional, clarifying instructions were occasionally provided by the researcher and clinical team regarding the position of the vest, feet and arms.

E2: **"I thought I need to lean back before getting up."**

E5: **"They (physiotherapists) haven't said anything about “moving over knees”. Maybe they don't want to upset me but if I need to do it in order to stand, why not? I could get up on my feet sooner.”**

E6: **“It was quite different. It was easier to get up by listening to this wee guy (avatar)”**

E7: **"Usually, they (physiotherapists) just grab me and push me up then ‘off you go’. I didn’t know I’d need to lean forward before standing-up".**

Like the provision of instructions, participants found the automated instructions were particularly helpful in recovering the movement and more supportive than feedback provided by staff.

E1: Participant mentioned their improvement of STS performance was due to knowing which factor to improve. **"What the wee guy (avatar) said helped me."**

E5: **"I feel this is beneficial to me", "I can see my results (conclusive feedback) on the screen, my improvement with my friend (avatar) but I can't with the girls (physiotherapists)", “I was barely able to stand-up**

when we first met. With this now I am able to stand confidently. I can go to the toilet on my own now".

E7: "**The system is very good. I like the graphs (conclusive feedback). Without its help, I won't be able to stand as good as I am now."** The support worker next to the participant said, **"I can see E7's improvement from it (conclusive feedback)."**

E8: **"I know I am having issues with my balance, but the physios wouldn't tell me. Good, this thing did!"**

Theme 3: Aesthetic appearance of the system and equipment

Some participants find the vest that holds the inertial sensor was inspiring. They felt like stepping into a role of a marathon runner or like a soldier wearing a uniform, a symbol of sheer grit and determination. Each time when participant, E8, was wearing the vest, they recalled that they used to run marathons and ready to **"try harder than running a marathon"**. Participant, E5, named the vest as a "uniform". **"I am wearing my uniform**". They also mentioned the vest gave her a sense of pride and spirit.

Regarding the design of the inertial sensor, participant, E7, found it interesting that each time they had to be **"wired up"** with USB cables. The VR was **"fun"** and subject felt like they **"were sitting on a bus"**.

6.4.5 Effectiveness

The following section provides details of the recorded outcome measures, including TAT points, EMS scores, FTSTS tests and activity data. The results are presented in tabular and graphical formats and tested for statistical differences using appropriate tests depending on whether the data met the criteria for parametric testing.

6.4.5.1 Activity Data

Table 17 and 18 show the daily number of STS executions and steps conducted by all participants pre- and post-trial. The data were recorded by ActivPAL sensors and taken 48 hours before and after the training interventions. The changes in the number of STS executions and steps are also presented in the tables. The results excluded movements captured during normal therapy practices.

Table 17: The number of daily STS executions and steps the experimental group participants conducted 48 hours before and after the study as recorded by the ActivPAL sensors and the changes in the number of STS executions and steps.

Participant	**Number of daily STS pre-trial**	**Number of daily STS post-trial**	**Changes in daily STS**	**Number of daily steps pre-trial**	**Number of daily steps post-trial**	**Changes in daily steps**
E1	18	31	+13	70	440	370
E2	13	22	+10	62	820	758
E3	13	16	+3	18	59	41
E4	8	63	+55	540	295	-245
E5	20	28	+8	182	452	270
E6	26	44	+19	404	3220	2816
E7	16	18	+2	242	330	88
E8	12	14	+2	10	50	40
E9	N/A	N/A	N/A	N/A	N/A	N/A
Median (IQR)	14.3 (7.63)	25.0 (24.5)	8.75 (14.9)	126 (335)	385 (610)	179 (621)

Table 18: The number of daily STS executions and steps the control group participants conducted 48 hours before and after the study as recorded by the ActivPAL sensors and the changes in the number of STS executions and steps.

Participant	**Number of daily STS pre-trial**	**Number of daily STS post-trial**	**Changes in daily STS**	**Number of daily steps pre-trial**	**Number of daily steps post-trial**	**Changes in daily steps**
C1	14	14	0	13	820	807
C2	N/A	N/A	N/A	N/A	N/A	N/A
C3	42	16	-26	335	687	352
C4	5	5	0	56	82	26
C5	33	4	-29	175	15	-160
C6	10	25	15	24	323	299
C7	4	4	0	1	0	-1
C8	19	2	-17	287	47	-240
C9	9	25	17	1	6	5
Median (IQR)	12.0 (23.5)	9.50 (18.8)	0.00 (34.0)	40.0 (255)	51.0 (255)	15.5 (355)

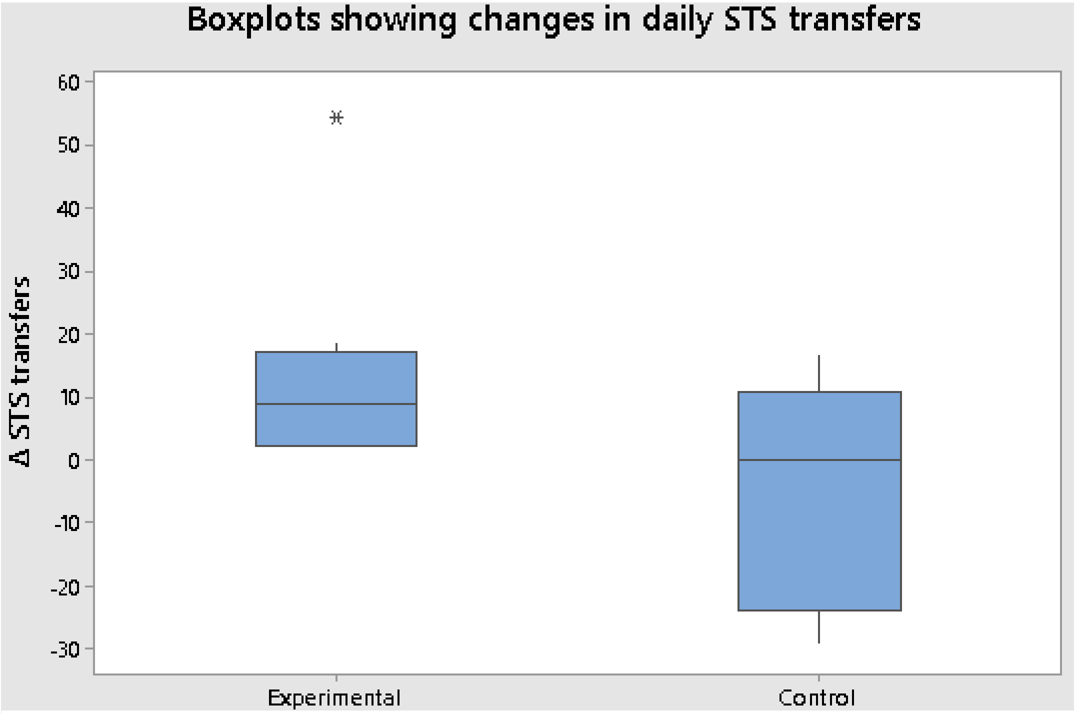


Figure 58: Boxplots show the minimum, first quartile, median, third quartile and maximum changes in daily STS transfers in the experimental and control groups.

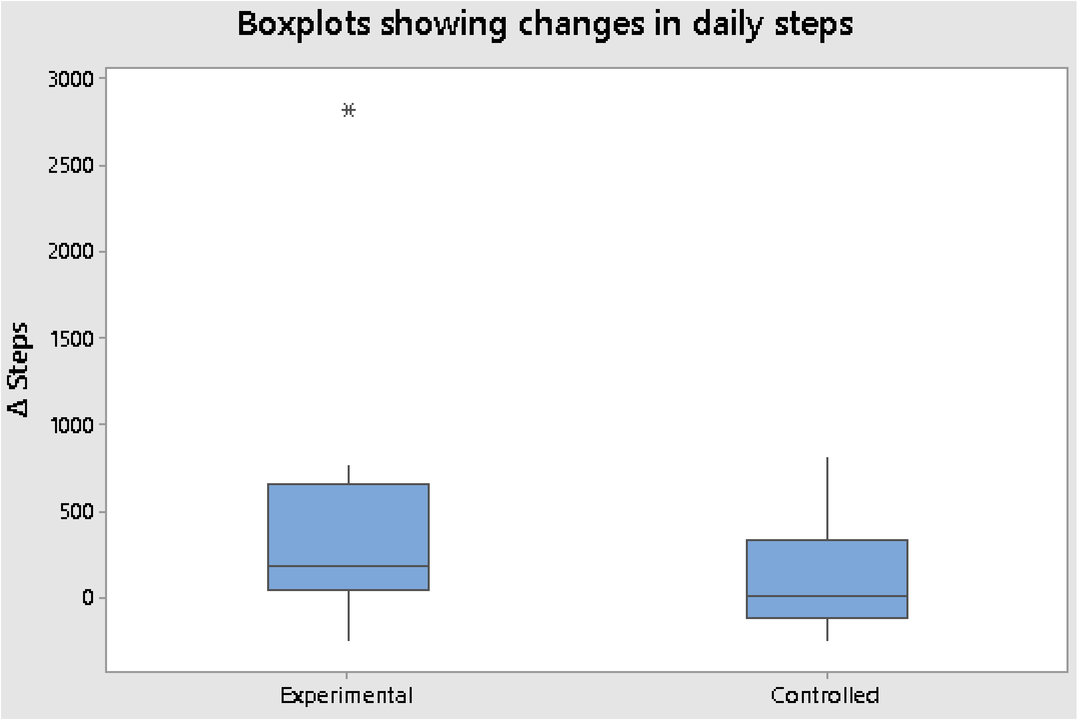


Figure 59: Boxplots show the minimum, first quartile, median, third quartile and maximum changes in daily steps in the experimental and control groups.

ANOVA (Analysis of variance) tests were conducted to compare the mean difference of the changes in daily STS movements and steps obtained from the experimental group and control group as shown in table 19.

Table 19: ANOVA tests on changes in daily STS and steps.

ANOVA Test	**Changes in daily STS movements**	**Changes in daily steps**
α = 0.15	0.046	0.313

The activity data were tested for a normal distribution. The p-values for the experimental group's results (both changes in daily STS movements and steps) were below 0.05. Hence, the data were not normally distributed. Therefore, Mann-Whitney tests (non-parametric tests) were conducted to test the null hypothesis that any selected value, either the changes in the number of daily STS executions or steps, in the experimental group (η1) will be greater than any samples in the control group (η2).

Number of daily STS executions recorded by the ActivPAL sensor:

The median change in STS daily movements was 8.75 in the experimental group compared to 0 in the control group. The difference was statistically different (p=0.0199).

Number of steps recorded by ActivPAL:

The median change in daily steps in the experimental was 179 steps, compared to 15.5 in the control group. The difference was not statistically significant (p=0.1592).

6.4.5.2 Clinical Outcomes Measures

Table 20 and 21 show the TAT points and EMS scores achieved by participants pre- and post-trial. These baseline measures were conducted on participants by the therapists and recorded on medical notes before the placement of ActivPAL sensors.

Table 20: The TAT and EMS achieved by the experimental group participants before and after the study.

Participant	Tinetti score pre-trial	Tinetti score post-trial	Changes in Tinetti score	EMS point pre-trial	EMS points post-trial	Changes in EMS points
E1	14	22	8	6	17	11
E2	4	24	20	1	16	15
E3	10	20	10	3	14	11
E4	14	25	11	5	15	10
E5	9	16	7	2	10	8
E6	9	25	16	4	20	16
E7	5	18	13	1	14	13
E8	5	13	8	0	5	5
E9	N/A	N/A	N/A	N/A	N/A	N/A
Mean (S.D.)	8.75 (3.92)	20.38 (4.44)	11.63 (4.50)	2.75 (2.12)	13.88 (4.58)	11.13 (3.60)

Table 21: The TAT and EMS achieved by the control group participants before and after the study.

Participant	**Tinetti score pre-trial**	**Tinetti score post-trial**	**Changes in Tinetti score**	**EMS point pre-trial**	**EMS points post-trial**	**Changes in EMS points**
C1	N/A	N/A	N/A	N/A	N/A	N/A
C2	5	6	1	4	4	0
C3	16	20	4	9	11	2
C4	7	8	1	2	6	4
C5	2	8	6	1	2	1
C6	9	19	10	3	11	8
C7	12	21	9	5	12	7
C8	18	20	2	11	13	2
C9	6	20	14	5	12	7
Mean (S.D.)	9.38 (5.55)	15.25 (6.61)	5.88 (4.76)	5.00 (3.42)	8.88 (4.33)	3.88 (3.11)

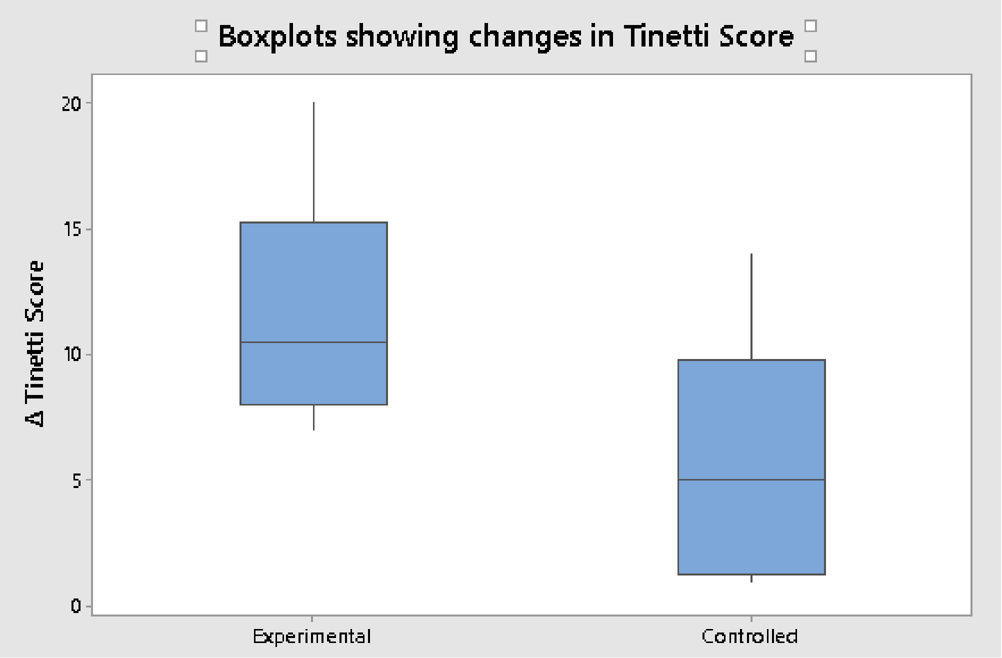


Figure 60: Boxplots show the minimum, first quartile, median, third quartile and maximum changes in TAT points in the experimental and control groups.

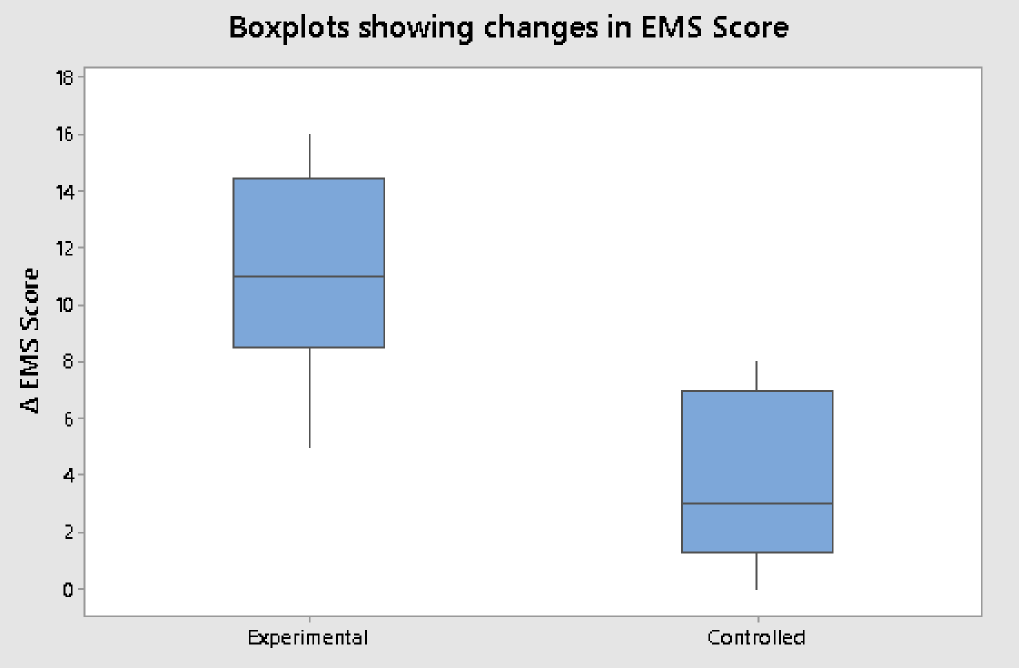


Figure 61: Boxplots show the minimum, first quartile, median, third quartile and maximum changes in EMS Score in the experimental and control groups.

ANOVA (Analysis of variance) tests were conducted to compare the means of the changes in Tinetti score and EMS points obtained from the experimental group and control group differ as shown in table 22.

Table 22: ANOVA tests on changes in TAT and EMS.

ANOVA Test	**Changes Tinetti**	**Changes in EMS**
α = 0.15	0.026	0.001

The clinical outcome measures were tested for a normal distribution. The p-values for the results (both changes in TAT points and EMS Score in both groups) were above 0.05. Hence, the data were normally distributed. Given the limited number of samples, therefore, t-tests were conducted to test the null hypothesis that any selected value, either changes in TAT points or the EMS scores, in the experimental group (η1) will be greater than a sample in the control group (η2).

<u>Tinetti Assessment Tool Points:</u>

The median change in TAT points was 11.63 in the experimental group compared to 5.88 in the control group. The test-statics value (t-value) was 2.48 which suggests the difference was statistically different.

Elderly Mobility Scale Score:

The median change in EMS Score was 11.13 in the experimental group compared to 3.89 in the control group. The difference was significant according to the test statics value (t-value = 4.39).

6.4.5.3 Five-Times-Sit-to-Stand Test

Table 23 and 24 show the results of the FTSTS tests which were conducted on participants before the placement of the ActivPAL sensor pre- and post-trial. The majority of participants were unable to complete all five-repetitions of the movement pre-trial, but only three control group participants couldn’t do so after the trial. The total time required for a participant to successfully complete the test is also shown in the tables.

Table 23: Results of the five-times sit-to-stand tests conducted on experimental group participants pre- and post-trial. All the results were measured in seconds.

Participant	**Five Times STS Results Pre-trial**					**Sum**	**Mean**	**Five Times STS Results Post-trial**					**Sum**	**Mean**
	1st STS	**2nd STS**	**3rd STS**	**4th STS**	**Sum**			**1st STS**	**2nd STS**	**3rd STS**	**4th STS**	**5th STS**		
E1	6.20					6.20	6.20	1.59	3.87	2.25	2.28	4.94	14.93	2.99
E2	8.55					8.55	8.55	1.45	2.03	4.65	2.78	3.17	14.08	2.82
E3	3.89	2.13				6.02	3.01	3.01	3.88	4.64	3.97	2.59	18.09	3.62
E4	5.16	4.19				9.35	4.68	3.58	2.95	4.57	4.99	5.81	21.90	4.38
E5	11.61	7.63				19.24	9.62	8.93	8.12	5.20	7.64	5.93	35.82	7.16
E6	Failed	4.30	5.94			10.24	5.12	1.42	1.16	0.73	0.82	1.17	5.30	1.06
E7	7.45					7.45	7.45	2.87	3.92	3.42	4.73	2.39	17.33	3.47
E8	3.79					3.79	3.79	4.71	3.84	6.28	4.13	5.34	24.30	4.86
E9	N/A							N/A						
					Mean **(S.D.)**		6.05 (2.33)					**Mean** **(S.D.)**		3.80 (1.77)

Table 24: Results of the five-times sit-to-stand tests conducted on control group participants pre- and post-trial. All the results were measured in seconds.

Participant	**Five Times STS Before Study**					**Sum**	**Five Times STS After Study**					**Sum**	**Mean**
	1st STS	**2nd STS**	**3rd STS**	**4th STS**	**5th STS**		**1st STS**	**2nd STS**	**3rd STS**	**4th STS**	**5th STS**		
C1	**N/A**												
C2	Failed	Failed	5.42				Failed	6.59					
C3	3.56	4.25	3.28	2.75	3.81	17.65	2.40	3.72	3.89	4.53	5.54	20.08	4.02
C4	5.74						4.92	6.24					
C5	3.58						4.32	2.97	3.82				
C6	10.12						4.17	2.40	3.22	2.92	4.53	17.24	3.45
C7	5.98						9.42	6.93	8.35	12.58	11.64	48.92	9.78
C8	Failed	Failed	2.02				3.69	3.81	5.72	6.28	4.14	23.64	4.73
C9	4.93	4.11					3.81	2.97	5.03	4.22	3.90	19.93	3.99
					Mean (S.D.)	N/A					**Mean (S.D.)**		5.19 (2.60)

6.4.6 Other Factors

This section is an analysis of factors which could explain the more positive results found in the experimental group apart from their participation in the technology augmented STS training.

6.4.6.1 Age

Younger participants in both groups tend to have a larger increase in the number of daily STS transfers than older individuals, while age was found to have no influence on the clinical outcome measures.

Table 25: Correlations between age and the increase in activity levels in both groups.

α = 0.15	**Age VS Change in daily STS (Experimental)**	**Age VS Change in daily STS (Control)**	**Age VS Change in steps (Experimental)**	**Age VS Change in steps (Control)**
p-value	0.126	0.145	0.106	0.977

Table 26: Correlations between age and the increase in functional test scores in both groups.

α = 0.15	**Age VS Change in Tinetti (Experimental)**	**Age VS Change in Tinetti (Control)**	**Age VS Change in EMS (Experimental)**	**Age VS Change in EMS (Control)**
p-value	0.226	0.488	0.435	0.188

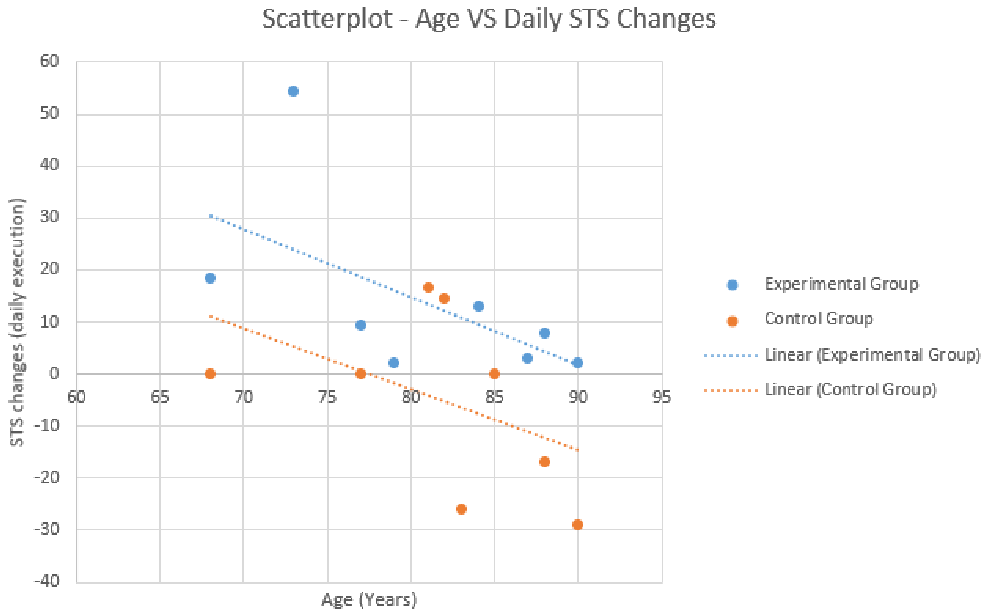


Figure 62: A scatterplot showing the correlation between the age of the experimental group participants and their changes in daily number of STS transfers.

6.5 Discussion

To our best knowledge from available literature, this is the first clinical trial evaluating the acceptability and effectiveness of a VR based system that provides a 3D-animated avatar in a real-life environment and feedback to assist the training of the STS movement in geriatric patients. The results of this randomised controlled trial demonstrate using the overall feedback system is safe and feasible in a clinical environment. Moreover, it is superior to standard physiotherapy in recovering the movement and improving general mobility.

The increase in STS activity was statistically significant in participants who practised with the system. They also showed to have tangibly better motor functions after the trial than the participants who trained with standard physiotherapy. The experimental group achieved a significant enhancement in their general mobility when comparing the group's TAT points and EMS scores to the control group.

An improvement in the ability to stand up independently and safely may have led to an improvement in general mobility, such as number of steps per day. This outcome was therefore worth measuring. However, the data suggest the system had no significant effect on increasing stepping activities. This is not unexpected as the system aims at restoring the STS movement only and there was no difference between the two groups in recovering gait movements. The clinical outcomes were recorded right before and after the trial. A follow-up assessment could be achieved, for example, three months, after the study to see whether the improvement in mobility has continued.

The average age of the participants in both groups is similar. The difference of the average age is just below 1 year. However, the control group started with a higher average TAT and EMS score.

A male participant in the experimental group who also the youngest was doing exceptionally well compared to all other females. In contrast, the only two male participants in the control group had not improved compared to the females in the same group. Participants who were admitted due to fractured hip(s) improved better and quicker than participants who admitted for other reasons (i.e. stroke, neuropathy pain and leg amputation).

The statistically significant improvement accomplished by the experimental group could have been influenced by the visual and auditory feedback, which participants found to be motivating, intuitive and enjoyable to have as part of their physiotherapy. The positive effects could be underpinned with the fact that feedback enhances motor relearning experience (Feys et al., 1998) (Koritnik et al., 2010) (Turolla et al., 2013) (van den Berg et al., 2016) and the overall feedback system increased the available feedback in various forms, knowledge of results and performance in real-time and at the end of the training session (i.e. conclusive feedback). In addition, the mirror feedback provided by an animated avatar, which participants found to be attractive, triggered interests and made the training sessions more pleasant. This improved outcomes and increased adhesion to therapy. In a few occasions, participants requested to repeat the augmented training session, implied to more active participation.

There were some limitations presented in this trial. During the study, there were 438 geriatric patients admitted to the ward. Almost all of them required some forms of STS training, and over half of them suffered from cognitive issues, thus, unsuitable to join the trial. Based on that figure, there were 219 eligible participants. Nonetheless, recruitment was not consistent across the clinical team. Therapists who were keen about recruitment were off sick and on holiday in a few occasions. Perhaps, a training or an educational session, which contains results from an earlier feasibility study, shall be provided to the clinical team in removing barriers and concerns about conducting a trial in the ward. Greater engagement with the clinicians before studies commence could also be considered. If they were part of the design process, they could be more likely to be engaged in the recruitment.

All participants in this trial were keen and interested to take part. Consequently, it is likely that they were already motivated towards training with technology. This gives a rise to the potential for bias. The size of the sample is too small to reflect the whole geriatric population and lacks the range of disabilities and comorbidities which could have resulted in different STS characteristics.

Participants in the experimental group received extra attention and the training was observed by the researcher closely. This could influence the results and was reported in other clinical trials as the Hawthorne effect (De Amici, Klersy, Ramajoli, Brustia, & Politi, 2000) (McCarney et al., 2007) (Berthelot, Le Goff, & Maugars, 2011) (McCambridge, Witton, & Elbourne, 2014). The control group did acknowledge that they were not trained with computer technology and received less attention. This could be a demotivating factor as they could know that they were provided with fewer incentives.

Moreover, the study protocol required the experimental group to receive augmented STS training only. However, when they received other physiotherapy and must be stood on their feet (i.e. attending gym sessions, gait and stair walking training), the clinical team still had to provide instructions and manual support for standing up.

Restrictions were also identified with the clinical outcome measures. Although, the FTSTS test was validated to be a reliable and robust functional test in assessing lower limbs strength (Goldberg, 2012) (Jordre et al., 2013) and mobility in the geriatric population (Duncan et al., 2011) (Annweiler et al., 2011) (Sutherland et al., 2016). In this clinical trial, the test was found to be inadequate when implementing on geriatric patients who have limited mobility. The standardised FTSTS test requires the subject to cross their arms over the chest and sit with their back against the backrest of the chair before standing up. None of the participants in this study could stand without holding on any aids (e.g. armrests and a Zimmer frame). It was unsafe for them to stand without holding onto supports as suggested by the clinical team. None of the participants could complete the FTSTS test pre-trial and only five out of eight control group participants could fully conduct all five STS transfers at the end of study. Therefore, the test was adapted accordingly (i.e. allowed to aid) so participants could accomplish the functional test.

Studies have shown the ActivPAL sensors provide “almost perfect” correlation and agreement with direct observation for the STS movement and stepping activities (Edwardson et al., 2017). The accuracy of its intelligent activity classification algorithm, which interprets its recorded accelerometer data into movement postures, is above 90% but not 100% accurate (Dowd, Harrington, & Donnelly, 2012) (Bassett et al., 2014) (Sellers et al., 2016) (Montoye et al., 2017). Therefore, the values of STS executions and steps recorded in this trial by the sensor could be over- or undervalued.

Standing time is worth including as an outcome measure as the number of steps is likely to be under reported given the very slow nature of some of the participants. Also, individuals may have simply stood up without walking, or taken small shuffling steps which may not have been picked up by the activity monitors.

This study is the one of the first clinical trials testing the feasibility and acceptability of a virtual reality system for training the STS movements in geriatric patients in a clinical rehabilitation setting. It has followed the process for developing a complex intervention (MRC framework) which is a cycle of development that includes an RCT to test the system’s feasibility and acceptability.

The group assignment of this trial was randomised. The participant assignment to the experimental group or the control group was purely based on chance rather than decided by the researcher or the participants in order to minimise possible bias. Therefore, the background of the two recruited groups of participants were similar except for the exercises they receive for STS recovery.

However, this was not a blinded RCT as participants and the outcome assessors were aware of the group assignments. Blinding in rehabilitation trials is difficult due to the need for cooperation from the participants. It is possible that participants in the experimental group performed better because they received extra attention. This has been known to influence research and was reported in other clinical trials as the Hawthorne effect (De Amici et al., 2000) (McCarney et al., 2007) (Berthelot et al., 2011) (McCambridge et al., 2014). The control group did acknowledge that they were not trained with computer technology and received less attention. This may have had a potentially negative effect on the control group which we were unable to measure, however we were aware of this potential effect on the findings.

Moreover, the study protocol required that the experimental group received STS training augmented with the training system only. However, when they received standard physiotherapy (e.g. attending gym sessions, gait and stair walking), the clinical team still provided instructions and manual support for standing up. All participants in this trial were keen and interested to take part.

They might already be motivated in training with technology. This gives a rise to the potential for bias. This may have contributed to bias toward the alternative hypothesises. Another important limitation of this study was the small sample size and only being conducted at a single clinical site.

At this stage of development of intervention, it is important to find out the feasibility and acceptability of such system. The scale of this RCT is small, however, it was easier and cheaper to correct mistakes and issues found in this study before employing the system in a multi-site large-scale clinical trial. For example, if there were issues found with the vest, it could be redesigned and replaced before adopting it in a larger clinical trial designed to test the efficacy of the system with sufficient statistical power.

With regards to the user centred design process, the acceptability and feasibility of the system were confirmed in this randomised controlled trial. The conceptual design (chapter 3) and detailed design (chapter 4 and 5) of the system were implemented and validated in a clinical environment.

6.6 Summary

A phase 2 randomised controlled trial was conducted at a geriatric rehabilitation unit to test the feasibility, acceptability and effectiveness of the developed computerised feedback system for regaining the STS movement in geriatric patients in a clinical environment. A total of 18 patients was recruited. They were randomised into an experimental or a control group.

The participants in the control group practised the STS movement manually with their therapists as usual and the experimental group practices the movement on the feedback system. Functional tests (Tinetti Assessment Tool, Elderly Mobility Score and Five-times-sit-to-stand test) were conducted 48 hours before and after the trial along with recorded daily STS and stepping activities by a digital activity monitor. Based on the post-trial functional tests (Tinetti Assessment Tool points and Elderly Mobility Score), participants who trained the STS movement on the feedback system improved significantly compared to the control group. Their daily STS movements was also increased significantly compared to the control group.

Chapter 7 – Discussion, Contributions, Limitations and Recommendations

This concluding chapter aims to summarise and discuss the key outcomes from the previous six chapters. In particular, the originality of the work and its potential impact on clinical practice will be discussed along with its limitations and consequent recommendations for future work, which seeks to improve the current training system and progress the integration of technology in the rehabilitation of older people.

7.1 Overview of the problems this thesis addressed

Mobility declines in old age and this is a key issue for older adults to maintain independence in activities of daily living (ADL) (Wolinsky et al., 2011) (Rantakokko, Manty, & Rantanen, 2013). Not only due to the natural process of ageing which could cause frailty syndrome (Chen, Mao, & Leng, 2014), other aging-associated diseases, such as stroke, Parkinson’s disease and arthritis, have a further negative impact on mobility (Manini, 2013). In particular, mobility impaired older adults find the STS movement, which is critical to ADL, is particularly difficult to complete (Gillette & Stevermer, 2012).

By practising this movement during physical rehabilitation, optimal STS performance can be regained again over time (J. H. Park, Kim, & Lee, 2015), thereby, potentially improving independence and physical activity. However, rehabilitation services are now being challenged by the increasingly aged population. This has created a bottleneck for access to rehabilitation services which have traditionally delivered the physical support and performance feedback needed to recover physical functions, such as the STS movement (Steihaug, Johannessen, Ådnanes, Paulsen, & Mannion, 2016). Technology may provide a solution by enabling greater practice of exercises and rehabilitation activities outside of the therapist led sessions. Many of these rehabilitation technologies have, in the past, not fully involved the end-users in their design and implementation and have, consequently, failed to be adopted into practices. Therefore, the focus of this project was to collaborate with stakeholders (patients, carers, therapists and a manager) to develop an STS training system for mobility impaired older adults that could be feasibly used in the clinical environment and was accepted to all users.

7.2 User-Centre Design Process

While there is clinical evidence suggesting the use of rehabilitation technologies could help to regain functional movements (for a full review see chapter 2), nevertheless, their adoption is slow with only a small percentage of them being adopted into either the clinical environment or home environment (A.-M. Hughes et al., 2014). In order to reduce the risk of failure due to poor design and bad usability, this project employed the user-centred design (UCD) process and engaged all the stakeholders in physical rehabilitation. The principles of the UCD were adhered throughout the project, from developing an initial design specification and user requirements, generating engineering concepts (see chapter 3), through the technical implementation stage (see chapter 4 and 5) and clinical evaluation (see chapter 6). The UCD process has been adopted by many other researchers in developing healthcare technologies, such as phone applications (Mccurdie et al., 2012) (Schnall et al., 2016), health portals (Stanziola et al., 2015) (Runaas et al., 2017) and decision-systems (Crawford et al., 2002).

Although, the adoption of UCD in developing medical devices has been increasing (Martin et al., 2012). However, it has not been widely adopted in developments of rehabilitation technologies. For instance, all of the STS feedback training systems identified in the literature search (see chapter 2), had no evidence that users had been engaged in the design process, only some limited evidence of user involvement in the evaluation phase. This project adopted the UCD framework from the very beginning to identify the key user requirements for a computerised STS feedback training system. This approach meant features, such as grading performance and providing simple graphic feedback (e.g. bar charts), may have been missed if the development was based on a literature search alone. These user requirements are important, not just for acceptability, but for an efficient, effective (both cost and clinical outcome), safe and satisfying training system. Failure to include users in the initial design is deemed to be the main reason for the failure of adoption (Gulliksen et al., 2003) (Bastien, 2010) (Duarte & Guerra, 2012). Their involvement promotes user-friendliness of the system such that it can be easily self-administrated by users with physical impairments while minimising assistance required from others, efficient to use and operation can be easily learnt without any prior knowledge of information technology. During the UCD process, three key themes were identified and recognised throughout the implementation process of the new STS feedback rehabilitation system:

1. Automation technology,
2. Interaction with user-interaction,
3. Comfortability.

These design priorities were similar to those reported by Kerr et al., (2018) for adopting technologies into stroke rehabilitation.

7.3 Prototype Development

The outcome of the UCD process was the primary driver in the prototype development. Thus, when selecting from a range of potential technologies for capturing real-time kinematics, a wearable inertial sensor and a portable force plate were considered the best options due to low cost, easy-to-operate, portability and accuracy. These points were also agreed with Gong, Liu, & Yan, 2017.

The system was also built to run from a low cost (£220) portable personal computer (i.e. laptop). The inertial sensor was located in a pocket of a specially designed sleeveless garment, which was fitted to individuals with easy to adjust Velcro straps so that individuals with the use of only one hand could still use the system as suggested by users (see section 3.3).

7.3.1 Ease of Use

In a survey (Villalba-Mora, Casas, Lupiañez-Villanueva, & Maghiros, 2015) involving 876 healthcare professionals, the idea of using technologies in clinical practice was assumed to be time-consuming and this remains one of the main barriers for technology adoption (Villalba-Mora et al., 2015). The instruments adopted in this study supported the plug-and-play characteristic minimising the need for user intervention and further hardware and software configurations, reduced set-up time (i.e. less than five minutes) and easy-to-operate. Users only needed to plug in a USB cable into a mini-USB port and no further action was required. Problems with wireless pairing have been reported as a usability barrier (Uzun, Karvonen, & Asokan, 2007). In order to avoid this issue and repeatedly recharging batteries while keeping the system affordable, the wired inertial sensor was adopted.

In order to run the visual feedback system (VFS), users only had to plug in each device into a USB port and run the program by double-clicking the start icon. After the software was loaded (about 15 seconds), users could interact with the system under a WIMP (Windows, Icon, Mouse, Pull-down menu) interface, the most commonly known and used human-computer interface (Ebert, Van Der Veer, Domik, Gershon, & Scheler, 2014). Then, the VFS could be started by clicking a “start button”. For convenience, the initial readings of both devices were auto-zeroed and indicating user starting position without the need for a time consuming and potentially complex, additional calibration process. This set-up is less time consuming than the use of more traditional motion capture systems, such as the real-time STS feedback systems developed by Heiden and colleagues (2009) and Roosink et al., (2015), as discussed in section 2.7.

7.3.2 Feedback

Feedback systems have been used for identifying movement impairments and monitoring rehabilitation progress in upper-limb disorders (Xiao & Menon, 2014), gait recovery (Afzal, Oh, Lee, Park, & Yoon, 2015), balance training (Xu et al., 2017) and STS training as mentioned in chapter 2. These systems typically enable automated and precise performance analysis and produce feedback to users.

The general consensus from clinical research is that there are three main causes of a failed STS movement in the geriatric population. They are:

1. Poor weight-symmetry loading, which can cause a loss of balance (Cheng et al., 1998),
2. Insufficient leg muscle strength to push and counteract the full bodyweight (Lomaglio & Eng, 2005),

3. Inadequate postural coordination (i.e. lean forward) when standing from a sitting position (Boukadida et al., 2015b).

Existing STS feedback systems, such as the WeHab (Kennedy et al., 2011) and the Rehab@home system (Faria et al., 2015), only provide feedback for one of these criteria (i.e. balance). A real strength of the system developed during this project was the provision of performance feedback on all three criteria, giving users more information for future improvement and increasing the diversity of people who may benefit from using the system. Performance feedback for the three main factors was provided in real-time and at the end of training (i.e. conclusive feedback) to increase retention rate as discussed in section 2.6.1.5.

Both real-time and conclusive feedback was desired by the users (see section 3.3) for motivation and to correct errors. This created technology challenges:

1. Tackle the signal processing issues for acquiring signals in real-time from the inertial sensor (i.e. accelerometer and gyroscope) and the force plate,
2. Detect real-time STS transitions (i.e. finite state machine),
3. Provide feedback from analysing the detected real-time kinematics (i.e. fuzzy inference system).

Stakeholder engagement was the key to overcoming these technical challenges and ensure the resulting feedback was useful and instructive. Mobility-impaired older adults (n = 5) attended evaluation sessions to test the reliability and acceptability of a range of developed solutions as detailed in section 4.2.3 and 5.5. The involvement of these users was critical as testing the solutions on healthy adults, who have different STS kinematics (as detailed in section 2.3) and better physical mobility, might not reflect their true performance and feasibility correctly. Algorithms designed to detect kinematic events and analyse movements and provide feedback are frequently only tested on healthy individuals (Dejnabadi, Jolles, Casanova, Fua, & Aminian, 2006) (Leach et al., 2014) (Salah et al., 2014) (Cippitelli et al., 2015) (Wang, Kurillo, Ofli, & Bajcsy, 2015) (Kanai et al., 2016) (Filippeschi et al., 2017), an approach which risks a flawed outcome when applied to impaired individuals.

7.3.3 Clinical Evaluation

As discussed previously in section 3.3, feasibility and clinical evidence are the keys to the adoption of technology as found in another study (Tarricone, Boscolo, & Armeni, 2016). Therefore, a pilot randomised controlled trial was conducted at a geriatric rehabilitation unit with patients who had impaired mobility that prevented them from living independently, including an impaired ability to stand-up from a chair. The aim of this trial was to test the system's feasibility and acceptability as well as to gather preliminary evidence of efficacy.

As detailed in chapter 6, the findings demonstrated that the STS training system was feasible in the clinical environment. The ratio of training sessions offered and training sessions attended was high with 100% of all possible sessions successfully completed. This rate is higher than most VR studies in the older population which is around 70% (Miller et al., 2014). Moreover, patients in the experimental group recovered mobility functions better and had a higher number of increased daily STS repetitions than the control group. The median change in STS daily movements was 8.75 in the experimental group compared to 0 in the control group, this difference was statistically different (p=0.0199). The median change in TAT point was 11.63 in the experimental group compared to 5.88 in the control group which suggests the difference was statistically different (t = 2.48). The median change in EMS score was 11.13 in the experimental group compared to 3.89 in the control group (t = 4.39) which also suggests the difference was significant.

It is not possible to make direct comparisons of these results with other similar rehabilitation technologies due to the range of outcome measures used (Da-Silva, Moore, & Price, 2018). There is a general lack of clinical studies testing the use of technology in regaining the STS movement and there are no studies comparing technology-based training with standard physiotherapy.

While accepting the limitations of the clinical trial (discussed in the next section), this initial study comparing standard and technology-enhanced STS training has:

1. Demonstrated the system is acceptable to users (geriatric patients and the clinical team),

2) Demonstrated it can be feasibly deployed in a clinical rehabilitation unit,

3) Improved STS ability and general mobility as measured by the TAT and EMS, compared to standard therapy,

4) Improved the physical activity of the STS movement.

The exact mechanism behind these promising results would warrant future research but increased motivation and engagement with the system was widely reported by the users and would seem a likely cause for the improved motor performance and increased the level of activity, a finding reported by others (A. Li, Montaño, Chen, & Gold, 2011) (David J. Reinkensmeyer & Boninger, 2012)(Keime, Hays, Vazquez, Sauerwald, & Shwket, 2017) (Leblong, Fraudet, Dandois, Nicolas, & Gallien, 2017).

7.3.4 Costing and Commercialisation

The total cost of the system is shown in table 27:

Table 27: Cost of the equipment and the total cost of the system.

Equipment	**Cost**
Laptop	£350
Inertial Sensor	£50
Inertial Sensor Protection Case	£5
Balance Plate	£420
USB cables	£2
Vest	£1
Velcro straps	£1
Total	**£809**

The feasibility and acceptability of the system for clinical use has been confirmed in a randomised controlled clinical trial. However, before this prototype can be commercialised, a larger clinical trial must be achieved to establish the system's ability to provide genuine health benefits, both in a clinical environment and at homes. The system has to pass regulatory controls and obtaining the CE mark. This will increase the confident of investors before taking it to the next stage of development and commercial production.

An alternative balance plate, such as the Wii balance board, could be adopted into the system in replace of the Bertec balance plate to reduce the cost for the commercial version of the system. A low cost version of the system could incorporate a Wii Balance Board, cost estimated at £70, or similar.

Rather than using an inertial sensor developed and assembled by another manufacturer, it is possible to build and implement a self-made inertial sensor to reduce the cost as well while maintaining the accuracy and robustness of the system.

7.4 Limitations

7.4.1 Cognitive Bias

The participants who took part in this project, from the analysis stage to the clinical trial volunteered their own time, resource and energy. This enthusiasm and commitment may have unwittingly introduced some bias when providing feedback on the system in that they held pre-existing positive beliefs on the potential for technology to improve motor relearning. It should be borne in mind that this view may not reflect the whole population of potential rehabilitation technology users. It is, nevertheless, improved position from which to judge the acceptability of a technology than one devoid of user input (Lu et al., 2011) (Martin et al., 2012) (Klompmaker et al., 2013). The therapists' perception of the STS training system is similar to what was reported by Tousignant et al. (2011).

However, bias from therapists with strongly held views on the use of technology in rehabilitation, for example, a belief in traditional hands-on approach could have impacted on the project from the user design process to the clinical evaluation. In fact, engaging healthcare professional participating in clinical trials have been report as a possible obstacle (Bower et al., 2014). This was identified as a possible factor in the relatively low recruitment rate, as discussed in section 5.6.

In this study, some therapists were more engaged in this process and offered valuable comments, such as the design preferences mentioned in section 3.3. Other therapists, however, were not as engaged. This may be because research activity is not a mandated part of their workload or perhaps some individuals lack interest in research and do not recognise its important to future rehabilitation.

7.4.2 Signal Processing

This study presented a novel sensor-fusion algorithm for capturing and integrating upper-trunk kinematics and ground reaction force (GRF) when standing-up. The use of a single inertial sensor to represent the whole body was felt necessary to meet the easy-to-use criterion, however, this required a number of assumptions and undoubtedly affected the fidelity of the data. For an accurate representation of the human body during the STS movement, inertial sensors would be required to be placed on each moving segment. Perhaps, a higher-grade inertial sensor with better electrical characteristics (lower noise, better response and reduced non-linearly) could be adopted. However, these changes would drive up cost (a high-grade inertial sensor could cost >$200) which would impact on cost-effectiveness and place a financial barrier to their use. Moreover, it would reduce the efficiency of the algorithms in dealing with real-time estimations. A more expensive laptop with higher processing power might be needed.

The performance of the sensor-fusion algorithm, STS detection algorithm and the automated feedback generation system were confirmed on mobility impaired older adults with the algorithm identifying the STS transitions and abnormities correctly during the trials according to the visual observations of the clinical team. Nevertheless, involving a larger number of participants with a broad range of patients (e.g. prosthetic users) would help to improve the accuracy of the algorithms by testing it across a larger range of STS movement profiles.

7.4.3 Hawthorne Effect

The trial results, both the experimental group and control group, could also be influenced by the Hawthorne effect, which has been reported in other clinical trials (De Amici, Klersy, Ramajoli, Brustia, & Politi, 2000) (McCarney et al., 2007) (Berthelot, Le Goff, & Maugars, 2011) (McCambridge, Witton, &

Elbourne, 2014), through the raised awareness of the STS movement. However, the lack of change in the control group suggests any effect was minimal for these participants.

Some of the participants were unable to complete the 4-week intervention period due to early discharge which could not be predicted. Resource limitations meant the researcher could not set-up the training system at their homes or care centres to continue with the training until the 4-week period was completed. This may have diluted the effect of the intervention but is typical of a public health service, future studies should be designed to statistically factor this into the analysis (e.g. an intention to treat model or design a study which includes a mixture of home and hospital delivered interventions).

7.4.4 Evidence for Home-Use

Other feedback training systems have reported having high acceptability of home-use for self-management (Leblong et al., 2017) (Standen et al., 2017) (Da-Silva et al., 2018). Based on the outcome of the feasibility study (see chapter 5), the visual feedback system has the potential to be utilised in the home environment and could fit into the telerehabilitation models. This is important for patients who have limited access to therapists, for instance, patients who live in remote areas or have poor access to transport (Dew et al., 2013).

At the moment, the lack of evidence for using the system at home prohibits any recommendation, despite, the encouraging feedback. An extension of the current work would be necessary to include a home-based rehabilitation trial to test for the system's acceptability in this environment and its effectiveness to improve the STS movement independently, without supervision.

The design of the clinical trial study was an RCT which is designed to test the efficacy of an intervention. It might have been worth doing a series of case studies with individuals, for example, provide the system to a patient and train at home and obtain their feedback. This design may have given richer data on individuals but has some limitations for statistics due to low numbers and lack of control (Barton, 2000).

7.4.5 Further Tailoring of Feedback

The current system provides feedback on STS movement performance. It may be valuable to include an additional stage to tailor the feedback more closely to individuals. Before the training program begins, users could practise the STS movement while their kinematics were captured and analysed by the system. This analytical information then "feedforwarded", which has been explored by rehabilitation studies (Saunders & Vijayakumar, 2011) (Kora, Lu, & McDaid, 2014), to a difficulty selection system that could determine a suitable difficulty mode and level for practising without being screened by therapists. It could set different parameters of acceptable practising range for each performance evaluation factor to ensure the system is adaptable and tailored to individual needs.

The customisation could also be achieved to the system if the user or therapist prefer to self-adjust the practising goals. This is possible for future iterations of the design and implementation process. Practising goals, such as the number of STS executions, time limits and lean angles, could all be adjusted by therapists to fit the individual user. This could enable therapists to have more control with the feedback system to suit their therapy program. However, the development process would require greater input from therapists in order to set the correct therapeutic goal based on their professional knowledge and experience in rehabilitation. More work has to be achieved to design, modify and validate the system user interface too, for example including a graded mechanical device for support users with little functional movement.

As discussed in section 2.6.1.5, when feedback is delivered too frequently, it may negatively interfere with motor relearning and skill retention. Therefore, in the future, it may be valuable to introduce automatic gradual reduction in feedback according to the user's performance and can be manually adjusted by therapists.

A set of suggested customisable criteria are:

- Number of STS executions to be executed in a training session. This may relate to an individual's endurance,
- Minimum and maximum training time per training session,
- Reduction of feedback provided in real-time.

7.5 Conclusion

The aim of this thesis was to design and test a rehabilitation technology that optimises training of the STS movement in a geriatric rehabilitation population and promote self-management. The design of such a device shall be informed by the patients' and healthcare professionals' perceptions and experiences of recovering this important movement through rehabilitation. The system shall be feasibly delivered within the current clinical model.

This thesis has produced an STS training system which fulfils this aim. Firstly, the design features of an STS rehabilitation system from the perspectives of stakeholders of geriatric rehabilitation were investigated. The participants acknowledged the needs for such system and informed that real-life stimulus (i.e. virtual reality environment), use of mirror feedback (i.e. an avatar) and the provision of feedback were the most important design features.

A new bespoke sensor-fusion algorithm and an STS detection algorithm were developed for measuring STS kinematics in mobility-impaired older adults. A feedback generation platform, consists of an automated feedback generation system (AFGS) and a VR-based visual feedback system (VFS), was also implemented. The accuracy of them in measuring kinematics and producing feedback was confirmed with five mobility-impaired older adults in feasibility studies.

The acceptability, feasibility and efficacy of the system was tested in a randomised controlled trial. The results suggested the system can be feasibly delivered within the current clinical model. The measured daily STS movements in the experimental group was increased significantly compared to the control group. One of the reasons could be the computerised feedback was more motivating than the feedback provided by therapists. In fact, a participant (see section 6.4.4.1) suggested that the computerised feedback was more believable than the feedback provided from their therapists. The extra real-life stimuli (i.e. virtual reality) and mirror feedback (i.e. avatar) could also provide extra motivational values and explained the encouraging outcome.

Hawthorne effect could have affected the participants in the experimental group as they received extra attention and the training was observed by the researcher closely. Although, the participants in the experimental group did not receive manual STS training from the therapists, however, instructions and feedback for their STS movement was still provided when they took part in other rehabilitation activities, for example getting out of bed to walk. These cofounding factors could affect the finding of the trial.

7.6 Thesis Contributions to Knowledge and Innovation

This thesis presents the need for, the development of, and the clinical evaluation of a technology-based automated feedback system for retraining the STS movement in older adults with mobility impairments. The novel system, developed through an iterative process of user involvements, was designed to meet a short list of criteria intended to make the translation into routine practice more likely.

This project was the first to investigate the design features of an STS computerised rehabilitation system from the perspectives of end-users, who universally acknowledged the needs for the developed feedback rehabilitation system and gave support to such system being used to deliver intensive practice of the STS movement in mobility-impaired older people. For instance, the needs for real-life stimulus, use of mirror feedback (i.e. an avatar), provision of real-time and conclusive were all identified as new design features emerged from the process.

A new bespoke sensor-fusion algorithm and an STS detection algorithm were developed to solve the signal processing issues related to raw acceleration, gyroscopic and force data. Both algorithms were dedicated for measuring STS kinematics in mobility-impaired older adults. A validation study was conducted. Using data measured with a gold-standard motion capture system on five mobility impaired older adults with a history of stroke, the accuracy and reliability of the algorithms were determined. With the low-cost inertial sensor (i.e. $50), the average mean errors of the sensor-fusion algorithm when measuring roll angles were 2.8 degrees and 1.7 degrees when measuring pitch angles. The average mean error was 0.094 ms^{-1} when measuring vertical velocity. There was a mean delay of 0.15 to 0.21 seconds when detecting the STS transitions between various phases. These errors are lower than other studies on using sensor-fusion algorithm (as detailed in section 4.4) in detecting human motions, despite a low-grade inertial sensor was adopted in this study. The finding suggests that the sensor-fusion algorithm and the STS detection algorithm are reliable and have satisfactory estimation accuracy. The use of these sensors found to increase motivation, adherence and intensity of practises as suggested by Burridge et al., (2017).

In this project, a feedback generation platform was also implemented. The feedback system consisted of an automated feedback generation system (AFGS) and a visual feedback system (VFS). Their design was carefully considered based on the user requirements captured from the analysis and designing stage. The fuzzy-logic based AFGS can distinguish STS performance based on three key factors to a successful STS movement: force-symmetry, impulse generated when rising and trunk forward lean. The accuracy of the system in producing feedback was confirmed with five mobility-impaired older adults with a history of stroke.

The encouraging outcomes from the clinical trial in terms of acceptability, feasibility and efficacy should be considered along with the limitations of a small, potentially biased, sample. Improving the ability of older adults to stand up safely from a chair has potentially huge implications for an individual’s ability to live an independent life as well as the care burden placed on society. The system presented in this thesis benefited from close collaboration with end-users and represents a substantial step forward in providing a technology-based solution for recovering this important functional movement.

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Appendix 1.1 - Participant Information Sheet for the Design Study (Patients)

Appendixes

Participant Information Sheet – Group (i) Stroke Survivors

Name of department: Biomedical Engineering

Title of the study: Development of a therapeutic rehabilitation system for restoring sit-to-stand movements in stroke survivors - questionnaire and interview stage

Short title: FIRST (Feedback Integrated Rehabilitation for Stroke Therapy)

Introduction

We are a group of researchers at the University of Strathclyde interested in improving recovery of mobility after a stroke. This particular project is being conducted by Mr. Siu Fai Ho ("Sunny"), who is a research student supervised by Dr Andy Kerr and Dr Avril Thomson in the Biomedical Engineering department. Contact details: Telephone: 0787 976 4882; Email: siu.ho@strath.ac.uk.

What is the purpose of this investigation?

Standing up from a chair can be difficult for many people after a stroke, we know that practicing the movement with therapists can improve this. We are interested in developing equipment to help people practice this movement by giving them the support needed as well as information on how well they are doing. Before we start building this equipment we would like to get more information from people who might use it.

The purpose of this study is simply to collect your experiences of rehabilitation and your opinions on some of our ideas for sit-to-stand training equipment.

Do you have to take part?

We are looking for participants who have had a stroke affecting their ability to stand, even if mobility equipment or help from another person is needed.

Appendix 1.1 - Participant Information Sheet for the Design Study (Patients)

Whether you decide to take part or not is entirely your own decision and will not have any bearing on any of the health or social services you may be receiving. If you do decide to take part but later change your mind this is entirely up to you and again this decision will not have any consequences for you.

What will you do in the project?

If you decide to take part in the study, we will arrange a suitable time to talk to you together with other stroke survivors and carers. We will arrange this at a convenient time and location. The complete session will be the maximum of 45 minutes.

When you arrive and are settled, the researcher will lead the interview by explaining the purposes and aims of the study. After the introduction, you will be invited to fill out a form regarding your personal details, including; age, gender, time since stroke, first part of your post code, use of mobility aides and severity of mobility restrictions. The questionnaire will take about 15 minutes to complete.

After that, you will be invited to join a focus-group interview with four to five participants. The interview will last about 20 minutes. We will discuss your experiences of rehabilitation, including the use of equipment and technologies, such as video games, treadmill and balance plates. Finally, we will show you some of our ideas to develop sit-to-stand training equipment and ask for your feedback. All the information will be recorded on paper and by digital audio equipment. At the end of the interview, you are free to go.

Refreshments will be provided.

If you cannot attend the interview but would like to take part in the study, you can complete a questionnaire based on the interview. We can send a copy of a questionnaire to you by email, post or access it via a web link. You can return the questionnaire by post to the researcher, a stamped addressed envelope will be provided (Mr Siu Fai Ho, Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.) or email (siu.ho@strath.ac.uk).

Unfortunately, we are not able to provide payments for your time or reimburse any expenses you may have incurred using public or private transport.

Why have you been invited to take part?

Appendix 1.1 - Participant Information Sheet for the Design Study (Patients)

As a stroke survivor with recent experience of rehabilitation, your opinions are very valuable to us in the design of a new training system for sit-to-stand. We are looking for individuals who are currently well, happy and able to be interviewed, and/or complete a questionnaire in English.

What are the potential risks to you in taking part?

If you are not used to being interviewed for a period of time as long as 20 minutes, you may find it tiring. Regular breaks will be provided with refreshments, such as water, tea and biscuits. Some of the questions may involve mental analysis (For example, commenting on the new design) and if you feel tired or uncomfortable of answering some of the questions, you are more than welcome to skip any questions or terminate the interview at any time without having to give a reason and without any consequences.

What happens to the information in the project?

We will use a unique code for each individual who participates in the study so all the information you provided will be kept anonymous. All information, along with any notes and recorded audio files, in written form and electronic form, will be stored in a locked cabinet in the Department of Biomedical Engineering. After completion of this study, the data will be destroyed.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

What happens next?

If you are interested in participating in the study please contact Mr Siu Fai Ho (Sunny) (siu.ho@strath.ac.uk or 0787 976 4882) and we will arrange a suitable time for the interview as well as answer any questions you may have. If you have decided not to participate we would like to thank you for reading this information sheet and considering our research.

When we have finished collecting all the information we will analyse the results and send you a report.

Appendix 1.1 - Participant Information Sheet for the Design Study (Patients)

Chief Investigators Details:

Dr Andy Kerr, Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.

Telephone: 0141 548 2855

Email: a.kerr@strath.ac.uk

Dr Avril Thomson, Department of Design, Manufacture and Engineering Management (DMEM), University of Strathclyde, Level 7, James Weir Building, 75 Montrose Street, Glasgow, G1 1XJ, U.K.

Telephone: 0141 548 2354

Email: avril.thomson@strath.ac.uk

Researcher Contact Details:

Mr. Siu Fai Ho (Sunny),

Address: Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.

Telephone: 0787 976 4882

Email: siu.ho@strath.ac.uk

This investigation was granted ethical approval by the University of Strathclyde Ethics Committee.

If you have any questions/concerns, before, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Linda Gilmour
Secretary to the Departmental Ethics Committee
Department of Biomedical Engineering
Wolfson Centre, 106 Rottenrow
Glasgow G4 0NW
Tel: 0141 548 3298 E-mail: linda.gilmour@strath.ac.uk

Thank you very much for reading this information – please ask any questions if you are unsure about what is written here.

Appendix 1.1 - Participant Information Sheet for the Design Study (Patients)

Consent Form

Name of department: Biomedical Engineering

Title of the study: Development of a therapeutic rehabilitation system for restoring sit-to-stand movements in stroke survivors - questionnaire and interview stage

Short title: FIRST (Feedback Integrated Rehabilitation for Stroke Therapy)

Group (i) Stroke Survivors

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.
- I understand that I can withdraw my data from the study at any time.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project
- I consent to being audio recorded as part of the project

(PRINT NAME):	Hereby agree to take part in the above project
Signature of Participant:	Date:

Appendix 1.2 - Participant Information Sheet for the Design Study (Healthcare Professionals)

Participant Information Sheet – Group (ii)
Healthcare Professionals

Name of department: Biomedical Engineering

Title of the study: Development of a therapeutic rehabilitation system for restoring sit-to-stand movements in stroke survivors - questionnaire and interview stage

Short title: FIRST (Feedback Integrated Rehabilitation for Stroke Therapy)

Introduction

We are a group of researchers at the University of Strathclyde interested in improving recovery of mobility after a stroke. This particular project is being conducted by Mr. Siu Fai Ho ("Sunny"), who is a research student, along with Dr Andy Kerr and Dr Avril Thomson in the Biomedical Engineering department. Leave the contact details until the end (Telephone: 0787 976 4882; Email: siu.ho@strath.ac.uk), if you are interested in participating in the study.

What is the purpose of this investigation?

As you will know standing up from a chair can be difficult for many people after a stroke, we know that practicing the movement with therapists can improve this. We are interested in developing equipment to help people practice this movement by giving them the support needed as well as information on how well they are doing. Before we start building this equipment we would like to get more information from people who might use it.

The purpose of this study is simply to collect your professional views of rehabilitation and your opinions on some of our ideas for sit-to-stand training equipment.

Appendix 1.2 - Participant Information Sheet for the Design Study (Healthcare Professionals)

Do you have to take part?

We are looking for participants who have had experience in the rehabilitation of stroke survivors. Whether you decide to take part or not is entirely your own decision and will not have any bearing on you. If you do decide to take part but later change your mind this is entirely up to you and again this decision will not have any consequences for you.

What will you do in the project?

If you decide to take part in the study, we will arrange a suitable time to talk to you. We will arrange this at the University of Strathclyde, Wolfson Centre, Biomedical Engineering department.

The first part of the individual interview is regarding your personal details, including; gender, occupation, years of experience, field of practice. The second part will ask for your views of stroke rehabilitation, including the use of equipment and technologies, such as video games, treadmill and balance plates. Finally, we will show you some of our ideas to develop sit-to-stand training equipment and ask for your feedback. The complete session will last about 30 minutes. At the end of the interview, you are free to go.

Refreshments will be provided.

If you cannot attend the interview and would like to take part in the study, you can still fill in a questionnaire based on the interview. We will send a copy of a questionnaire to you by email, post or access it via a web link. You can return the questionnaire by post to the researcher, a stamped addressed envelope will be provided (Mr Siu Fai Ho, Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.) or email (siu.ho@strath.ac.uk). If you are going to access the questionnaire via the provided web site, your answers will be saved automatically and you will not need to contact the researcher.

Unfortunately, we are not able to provide payments for your time or reimburse any expenses you may have incurred using public or private transport.

Why have you been invited to take part?

As a healthcare professional who has had experience in the rehabilitation of stroke survivors, your opinions are very valuable to us in the design of a new training system for sit-to-stand.

Appendix 1.2 - Participant Information Sheet for the Design Study (Healthcare Professionals)

What are the potential risks to you in taking part?

Some of the questions may involve mental analysis (For example, commenting on the new design) and if you feel tired or uncomfortable of answering some of the questions, you are more than welcome to skip any questions or terminate the interview at any time without having to give a reason and without any consequences.

What happens to the information in the project?

We will use a unique code for each individual who participates in the study so all the information you provided will be kept anonymous. All information, along with any notes and recorded audio files, in written form and electronic form, will be stored in a locked cabinet in the Department of Biomedical Engineering. After completion of this study, the data will be destroyed.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

What happens next?

If you are interested in participating in the study please contact Mr Siu Fai Ho (Sunny) (siu.ho@strath.ac.uk or 0787 976 4882) and we will arrange a suitable time for the interview as well as answer any questions you may have. If you have decided not to participate we would like to thank you for reading this information sheet and considering our research.

When we have finished collecting all the information we will analyse the results and send you a report.

Chief Investigator Details:

Dr Andy Kerr, Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.

Telephone: 0141 548 2855

Email: a.kerr@strath.ac.uk

Appendix 1.2 - Participant Information Sheet for the Design Study (Healthcare Professionals)

Dr Avril Thomson, Department of Design, Manufacture and Engineering Management (DMEM), University of Strathclyde, Level 7, James Weir Building, 75 Montrose Street, Glasgow, G1 1XJ, U.K.

Telephone: 0141 548 2354

Email: avril.thomson@strath.ac.uk

Researcher Contact Details:
Mr. Siu Fai Ho (Sunny),

Address: Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.

Telephone: 0787 976 4882

Email: siu.ho@strath.ac.uk

This investigation was granted ethical approval by the University of Strathclyde Ethics Committee.

If you have any questions/concerns, before, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Linda Gilmour
Secretary to the Departmental Ethics Committee
Department of Biomedical Engineering
Wolfson Centre, 106 Rottenrow
Glasgow G4 0NW
Tel: 0141 548 3298 E-mail: linda.gilmour@strath.ac.uk

Thank you very much for reading this information – please ask any questions if you are unsure about what is written here.

Appendix 1.2 - Participant Information Sheet for the Design Study (Healthcare Professionals)

Consent Form

Name of department: Biomedical Engineering

Title of the study: Development of a therapeutic rehabilitation system for restoring sit-to-stand movements in stroke survivors - questionnaire and interview stage

Short title: FIRST (Feedback Integrated Rehabilitation for Stroke Therapy)

Group (ii) Healthcare professionals

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.
- I understand that I can withdraw my data from the study at any time.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project
- I consent to being audio recorded as part of the project

(PRINT NAME):	Hereby agree to take part in the above project
Signature of Participant:	Date:

Appendix 1.3 - Participant Information Sheet for the validation study

Participant Information Sheet

Name of department: Biomedical Engineering

Title of the study: Development of a therapeutic rehabilitation system for movements in stroke survivors

Introduction

We are a group of researchers at the University of Strathclyde interested in improving recovery of mobility after a stroke. This particular project is being conducted by Mr. Siu Fai Ho ("Sunny"), who is a research student supervised by Dr Andy Kerr and Dr Avril Thomson in the Biomedical Engineering department. Contact details: Telephone: 0787 976 4882; Email: siu.ho@strath.ac.uk.

What is the purpose of this investigation?

Standing up from a chair can be difficult for many people after a stroke, we know that practicing the movement with therapists can improve this. We are interested in developing rehabilitation systems to help people practice this movement by giving them the support needed as well as information on how well they are doing. A prototype of the system has been developed. It is now important that we receive opinions and views to make sure it is fit for purpose.

The purpose of this study is simply to collect your opinions and views on a prototype game to improve your ability to stand up from a chair. During the game, information on how you move will be recorded and used to improve the game.

Do you have to take part?

We are looking for participants who have had a stroke affecting their ability to stand-up from a chair, even if mobility equipment or help from another person is needed. Whether you decide to take part or not is entirely your own decision and will not have any bearing on any of the health or social services you may be receiving. If you do decide to take part but later change your mind this is entirely up to you and again this decision will not have any consequences for you.

Appendix 1.3 - Participant Information Sheet for the validation study

What will you do in the project?

If you decide to take part in the study, we will invite you to our department at the University of Strathclyde. The complete session will be the maximum of 90 minutes. Transport will be arranged, if required.

When you arrive and are settled, the researcher will explain the purpose, procedure and activities to be conducted in the session. You will be given a demonstration of how to operate the game. All materials and equipment involved (e.g. cameras, sensors, force-plate, double-sided tape, reflective markers and chair) will be displayed and explained to you.

If you are happy to go ahead, the researcher will conduct a short 5 minute interview to gather your background information, including, age, gender, time since stroke and side of the body affected. You are free to skip any questions that you don’t want to answer.

If you are happy to continue, we will ask you to wear a pair of shorts and close fitting top (which we will provide and help you with, if needed) to which we will attach small markers. They are little foam balls, that mark important points of your body (feet, knees, hips, trunk, shoulders). Double sided tape will be used to attach the markers on your skin and clothing. Special cameras installed in the studio will record the movement of the balls. The result is a detailed analysis of your movements. We will also take some measurements of your body such as height, weight, and size of your joints. Once this is done, you will be asked to sit on a chair with armrests. The height of the chair is adjustable to fit your needs. An electronic sensor which produces light vibration will also be attached to your body. Cameras will be used to record the whole session. You will not be identified in the video recording. The video images of you will be obscured to prevent identification.

You will then be asked to start the video game with a mouse and a keyboard. This is a very simple game based around standing up and sitting down. The researcher will assist and stay with you throughout the exercise. Once the game has been started, you will repeat the standing-up and sitting-down movements for three times at your own pace. You will be able to see you movement on a computer screen along with messages and information about how you performed. After that, you can remain seated on the chair and rest for as long as you needed. After the resting period, you will be asked to repeat the previous step. Finally, the researcher will ask for your opinions on the game. At the end of the study session, you are free to go.

If you feel unwell or uncomfortable of having to repeat the movements for several times, you can rest for as long as you need or terminate the recording session, if you wish to do so.

Appendix 1.3 - Participant Information Sheet for the validation study

Refreshments will be provided.

Unfortunately, we are not able to provide payments for your time or reimburse any expenses you may have incurred using public transport or your own car. Transport can be arranged, if required. Please contact the researcher (Mr Siu Fai Ho, Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.) or email (siu.ho@strath.ac.uk).

If you have any questions about the study, please do not hesitate to contact us.

Why have you been invited to take part?

We are inviting people who have had a stroke affecting their ability to stand up from a chair. We are looking for individuals who are able to follow simple instructions, can communicate in English, can see with or without glasses, can attend a 90 minutes appointment at the University of Strathclyde. As the programme involves physical activity we are only recruiting people who are currently well enough to stand up from a chair on their own even with assistance. If you are unsure whether or not you are able to take part we would ask you to contact your GP or stroke liaison nurse who will be able to advise accordingly.

What are the potential risks to you in taking part?

If you are not used to standing up and down several times, you may find it tiring. You may experience mild aches and pains after the recording session. We hope to minimise this possibility by only asking you to stand up at your speed and levels of comfort. There is a risk of tripping or losing your balance. To prevent this, a researcher and a registered physiotherapist will stand very close to you during the recordings and your movement will be supported. This will not interfere with the camera view or game.

We will attach double-sided tape to your skin, occasionally this can cause a mild irritation similar to having sticky tape attached to your skin. This should only be a temporary irritation since the markers will only be in place for around 60 minutes.

During the session, if you feel tired or uncomfortable, you are more than welcome to terminate the session at any time without having to give a reason and without any consequences.

Regular breaks will be provided with refreshments, such as water, tea and biscuits.

Appendix 1.3 - Participant Information Sheet for the validation study

What happens to the information in the project?

We will use a unique code for each individual who participates in the study so all the information you provided will be kept anonymous. All information, along with any notes and the recorded files from the cameras, will be stored in a locked cabinet in the Department of Biomedical Engineering. After completion of this study, the data will be destroyed.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

What happens next?

If you are interested in participating in the study please contact Mr Siu Fai Ho (Sunny) (siu.ho@strath.ac.uk or 0787 976 4882) and we will arrange a suitable time for the recording session as well as answer any questions you may have. If you have decided not to participate we would like to thank you for reading this information sheet and considering our research.

When we have finished collecting all the information we will analyse the results and send you a report.

Researcher Contact Details:
Mr. Siu Fai Ho (Sunny),

Address: Department of Biomedical Engineering, University of Strathclyde,
Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.

Telephone: 0787 976 4882

Email: siu.ho@strath.ac.uk

Chief Investigators Details:
Dr Andy Kerr, Department of Biomedical Engineering, University of
Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.

Telephone: 0141 548 2855

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Dr Avril Thomson, Department of Design, Manufacture and Engineering
Management (DMEM), University of Strathclyde, Level 7, James Weir
Building, 75 Montrose Street, Glasgow, G1 1XJ, U.K.

Telephone: 0141 548 2354

Email: avril.thomson@strath.ac.uk

Appendix 1.3 - Participant Information Sheet for the validation study

This investigation was granted ethical approval by the University of Strathclyde ethics committee.

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Secretary to the University Ethics Committee
Research & Knowledge Exchange Services
University of Strathclyde
Graham Hills Building
50 George Street
Glasgow
G1 1QE

Telephone: 0141 548 3707
Email: ethics@strath.ac.uk

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

Appendix 1.3 - Participant Information Sheet for the validation study

Consent Form

Name of department: Biomedical Engineering

Title of the study: Development of a therapeutic rehabilitation system for movements in stroke survivors

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.
- I understand that I can withdraw my data from the study at any time.
- I understand that any information recorded in the investigation will be anonymised before shared openly or stored.
- remain confidential and no information that identifies me will be made publicly available.
- I consent to be a participant in the project
- I consent to be video recorded as part of the project and the information may be used for professional purposes, such as publication or presentation

(PRINT NAME):	Hereby agree to take part in the above project
Signature of Participant:	Date:

Appendix 1.4 – Participant Information Sheet for the RCT

Version 2, Date 30/12/2016

Contact Information: Mr. Siu Fai Ho
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Sit-to-stand exercise training with performance feedback

Participant Information Sheet

Introduction

We are a group of researchers at the University of Strathclyde interested in improving recovery of mobility. This particular project is being conducted by Mr. Siu Fai Ho (“Sunny”), who is a research student supervised by Dr Andy Kerr and Dr Avril Thomson in the Biomedical Engineering department. Contact details: Telephone: 0787 976 4882; Email: siu.ho@strath.ac.uk.

We’d like to invite you to take part in our research study, which is part of an educational qualification project. Whether you decide to take part or not is entirely your own decision and will not have any bearing on any of the health or social care services you may be receiving.

Before you decide we would like you to understand why the research is being done and what it would involve for you. The researcher will go through this information sheet with you, to help you decide whether or not you would like to take part and answer any questions you may have. If you do decide to take part but later change your mind this is entirely up to you and again this decision will not have any consequences. Please feel free to talk to others about the study if you wish.

The first part of the Participant Information Sheet tells you the purpose of the study and what will happen to you if you take part. Then we give you more detailed information about the conduct of the study. Do ask if anything is unclear.

What is the purpose of this investigation? Standing up from a chair can be difficult for many people, we know that practising the movement can improve this. We are interested in evaluating a video game that we have developed to help people practice this movement. It is now important that we test whether this helps or not.

If you decided to take part, you may be asked to join a control or experimental group. In the control group, you will practice sitting and standing-up as part of your normal exercise routine. If you join the experimental group, you will practice the same movements with the video game. All participants will need to wear a small activity monitor on their leg twice for 2 days each.

The study will last for 28 days and be conducted in your ward. Your involvement in the study will not affect any plans for you to go home.

Do you have to take part?

No. Whether you decide to take part or not is entirely your own decision and will not have any bearing on any of the health or social services you may be receiving. If you do decide to take part but later change your mind this is entirely up to you and again this decision will not have any consequences for you.

What's involved?

The purpose of this study is to test a new video game for training standing up from a sitting position. The game consists of an electronic sensor and a metal board which you will stand on. The sensor is small and lightweight. It will be placed inside a pouch on a loose vest which you will wear. This tells us how your body moves and how well you are doing while you are exercising with your therapist. We will use pictures and words to let you know your performance, for example, whether you are leaning too much on to the left.

Forty people will be invited for this study. Everyone will be separated into two groups. One group will have the usual treatment exercise from their therapist and the other will play the video game during the exercise sessions with the therapist. You would be expected to practice up to three times a week based on the recommendation from your therapist. No matter which group you belong to, you will need to wear an activity monitor on your thigh for 48 hours at the beginning of the study and again near the end of the study.

What will you do in the project?

If you decided to take part, we (the researcher) will first explain the purpose, procedure and activities to be conducted in this study with you. You will then be asked to read and sign a consent form.

We will perform a series of thinking and standing tests on you. They are already being used in your ward by your therapist. These assessments will not take more than thirty minutes in total to complete. An electronic physical activity monitor will be attached to your thigh by us. The monitor will be held by a film dressing. You expect to wear it 24 hours a day for 48 hours at the beginning of the study and again near the end of the study.

You will then be allocated to a group by the researcher. One group will practice with their therapist as normal. The other group will practice with the video game. Both groups are expected to practice the standing-up movements three times a week.

If you were chosen to practice with the video game. You will first be asked to sit on a chair with armrests. Then, you will be asked to wear a specially designed vest. Help will be available if needed. We will place a small box, which contains a sensor, in a pocket on the vest. Lastly, you will need to place your feet on a metal board. There will be a projected computer image showing your movements. When you play the game, you will hear the computer telling you what you should do. You can practise as long as you feel comfortable. If you feel unwell or uncomfortable about having to repeat the movement for several times, you can rest for as long as you need or stop the session as you wish.

Your therapist will supervise all training sessions. At the end of the study, you will be asked to repeat the same assessments that you achieved before the study.

Unfortunately, we are not able to provide payments for your time or reimburse any expenses you may have incurred.

If you have any questions about the study, please do not hesitate to contact us.

Why have you been invited to take part?

We are inviting people who have problems standing up from a chair. We are looking for individuals who are able to follow simple instructions, can communicate in English and can see with or without glasses. As the programme involves physical activity we are only recruiting people who are currently well enough to stand up from a chair, even if you need some help. If you are unsure whether or not you are able to take part, we would ask you to contact your therapist in the ward who will be able to advise accordingly.

What are the potential risks to you in taking part?

If you are not used to standing up and down several times, you may find it tiring. You may experience mild aches and pains after the training session. We hope to minimise this possibility by only asking you to stand up at your own speed and levels of comfort. There is a risk of tripping or losing your balance. To prevent this, your therapist will stand very close to you during practice and your movement will be supported, if needed.

To hold the activity monitor on your thigh we will use film dressing, which is water proofed and suitable for sensitive skin. However, this may cause a mild irritation similar to having sticky tape attached to your skin. If that is the case, the researcher will remove the monitor from you.

What happens to the information in the project? We will use a unique code for each individual who participates in the study so all the information you provided will be kept anonymous. All information, along with any notes, recorded files, will be stored in a locked cabinet in the Department of Biomedical Engineering. After completion of this study, the data will be destroyed.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

What will happen if I don't want to carry on with the study?

Appendix 1.4 – Participant Information Sheet for the RCT

If you don’t want to carry on with the study, you can inform the researcher anytime you want and you can be removed from the study at any time.

What will happen to the results of this study?

The results of this study will inform the performance of the video game. The anonymised data will be published in internal reports at the university, journals and/or conferences.

What happens next? If you are interested in participating in the study please contact Mr Siu Fai Ho (Sunny) (siu.ho@strath.ac.uk or 0787 976 4882) and we will arrange a suitable time for the recording session as well as answer any questions you may have. If you have decided not to participate we would like to thank you for reading this information sheet and considering our research.

When we have finished collecting all the information we will analyse the results and send you a report.

Researcher Contact Details: Mr. Siu Fai Ho (Sunny),

Address: Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.

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Email: siu.ho@strath.ac.uk

Chief Investigators Details: Dr Andy Kerr, Department of Biomedical Engineering, University of Strathclyde, Wolfson Building, 106 Rottenrow, Glasgow, G4 0NW, U.K.

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Dr Avril Thomson, Department of Design, Manufacture and Engineering Management (DMEM), University of Strathclyde, Level 7, James Weir Building, 75 Montrose Street, Glasgow, G1 1XJ, U.K.

Telephone: 0141 548 2354

Email: avril.thomson@strath.ac.uk

This investigation was granted ethical approval by the University of Strathclyde ethics committee.

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed, or further information may be sought from, please contact:

Secretary to the University Ethics Committee Research & Knowledge Exchange Services University of Strathclyde Graham Hills Building 50 George Street Glasgow G1 1QE

Telephone: 0141 548 3707 Email: ethics@strath.ac.uk

Appendix 1.4 – Participant Information Sheet for the RCT

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

Appendix 1.4 – Participant Information Sheet for the RCT

Version 2, Date 30/12/2016

Consent Form

Name of department: Biomedical Engineering

Title of the study: Sit-to-stand exercise training with performance feedback

Please tick the following boxes, if you agree:

☐ I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.

☐ I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.

☐ I understand that I can withdraw my data from the study at any time.

☐ I understand that any information recorded in the investigation will be anonymised before shared openly or stored.

☐ My details will remain confidential and no information that identifies me will be made publicly available.

☐ I consent to be a participant in the project

(PRINT NAME):	Hereby agree to take part in the above project
Signature of Participant:	Date:

Appendix 2.1 - Questionnaire for Patients

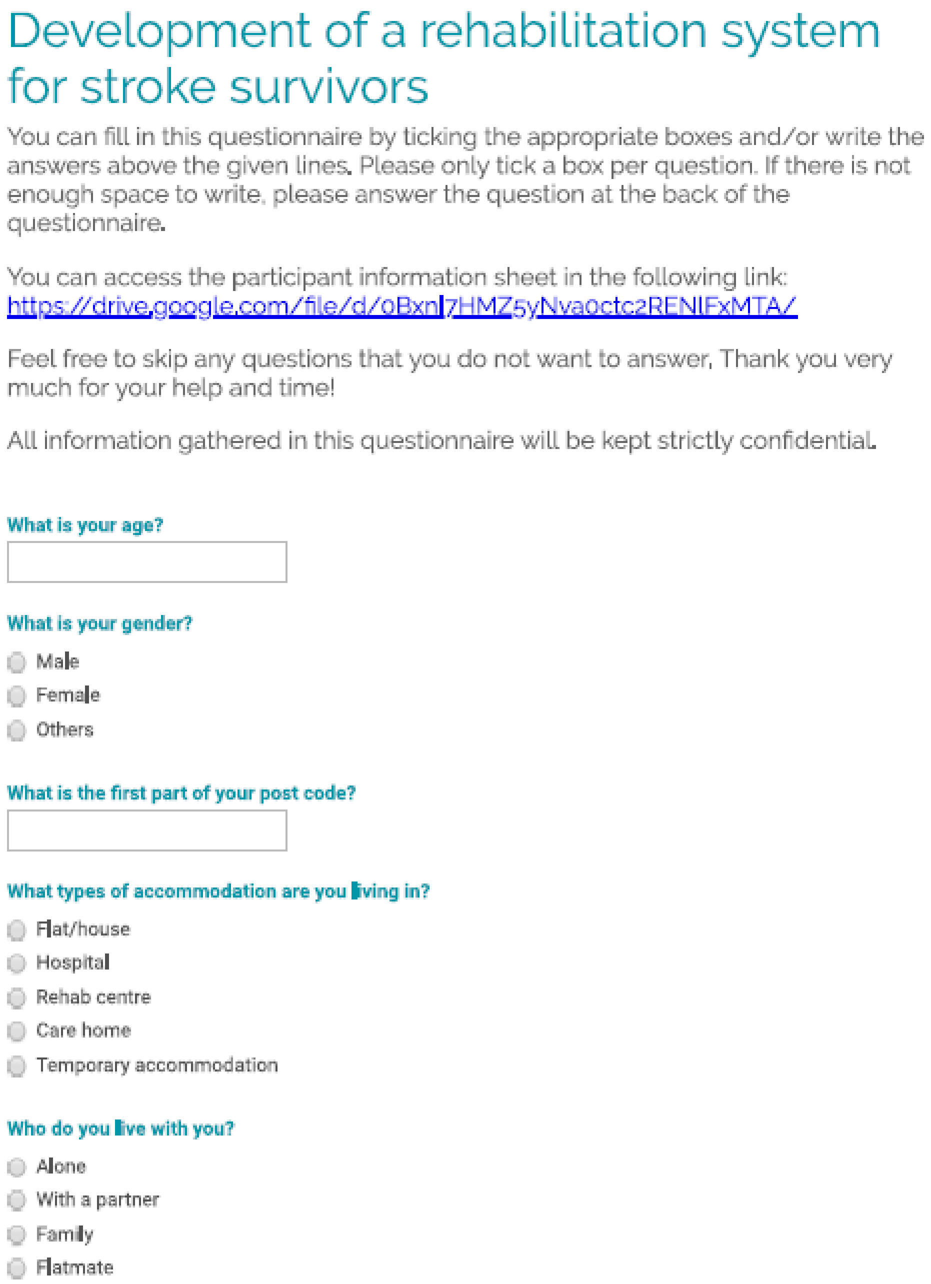
Questionnaire questions for group (i), stroke survivors

Title: Development of a therapeutic rehabilitation system for restoring sit-to-stand movements in stroke survivors.

Name of researcher: Mr Siu Fai Ho
Name of chief investigators: Dr Andy Kerr, Dr Avril Thomson

Q1. Do you find standing up from a chair difficult?
Q2. What is it that you find difficult?
Q3. Do you want to practice standing-up and sitting-down movements more often?
If yes, how much more often?
Q4. If there is a piece of sit-to-stand rehabilitation equipment that can be used at home for self-training, do you think you would use it?
Q5. Would you be happy to wear a small device for measuring movement that gives you more information about your body movements?
Q6. Have you ever worn an easy-wearing equipment (e.g. harness, straps)
If yes, what did you think of that?
Q7. Have you ever used a system that provides help moving from sitting to standing? (e.g. hoist, pulley system, ejector chair)
If yes, what did you think of that?
Q8. Have you ever used a computerised system that provides feedback for training your standing-up movement?
If yes, what did you think of that?

Appendix 2.2 – Questionnaire for Healthcare Professionals



Development of a rehabilitation system for stroke survivors

You can fill in this questionnaire by ticking the appropriate boxes and/or write the answers above the given lines. Please only tick a box per question. If there is not enough space to write, please answer the question at the back of the questionnaire.

You can access the participant information sheet in the following link: https://drive.google.com/file/d/0Bxnl7HMZ5yNva0ctc2RENlFxMTA/

Feel free to skip any questions that you do not want to answer, Thank you very much for your help and time!

All information gathered in this questionnaire will be kept strictly confidential.

What is your age?

☐

What is your gender?

○ Male
○ Female
○ Others

What is the first part of your post code?

☐

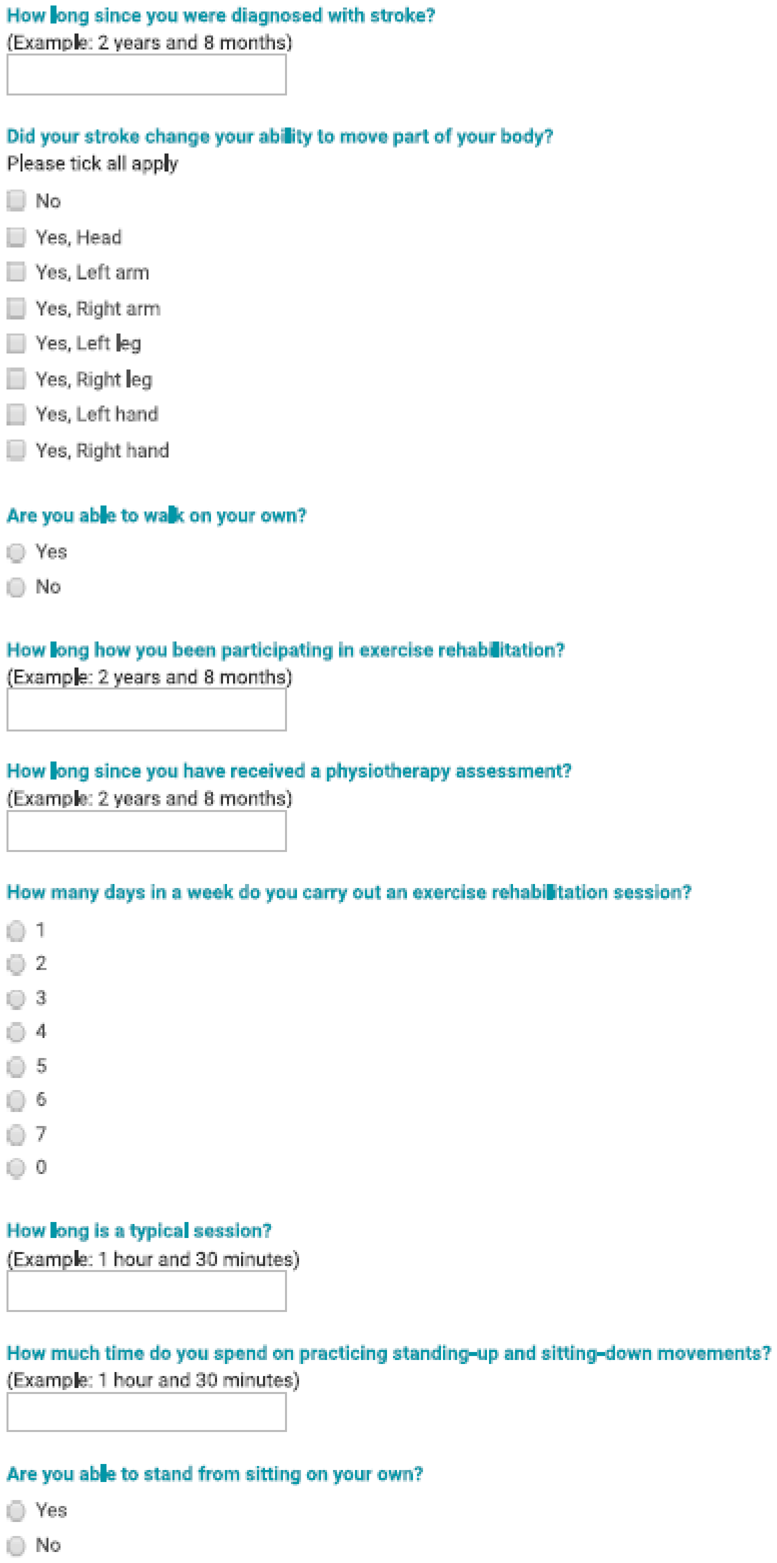
What types of accommodation are you living in?

○ Flat/house
○ Hospital
○ Rehab centre
○ Care home
○ Temporary accommodation

Who do you live with you?

○ Alone
○ With a partner
○ Family
○ Flatmate

Appendix 2.2 – Questionnaire for Healthcare Professionals



How long since you were diagnosed with stroke?
(Example: 2 years and 8 months)

Did your stroke change your ability to move part of your body?
Please tick all apply

- ☐ No
- ☐ Yes, Head
- ☐ Yes, Left arm
- ☐ Yes, Right arm
- ☐ Yes, Left leg
- ☐ Yes, Right leg
- ☐ Yes, Left hand
- ☐ Yes, Right hand

Are you able to walk on your own?

- ○ Yes
- ○ No

How long how you been participating in exercise rehabilitation?
(Example: 2 years and 8 months)

How long since you have received a physiotherapy assessment?
(Example: 2 years and 8 months)

How many days in a week do you carry out an exercise rehabilitation session?

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6
- ○ 7
- ○ 0

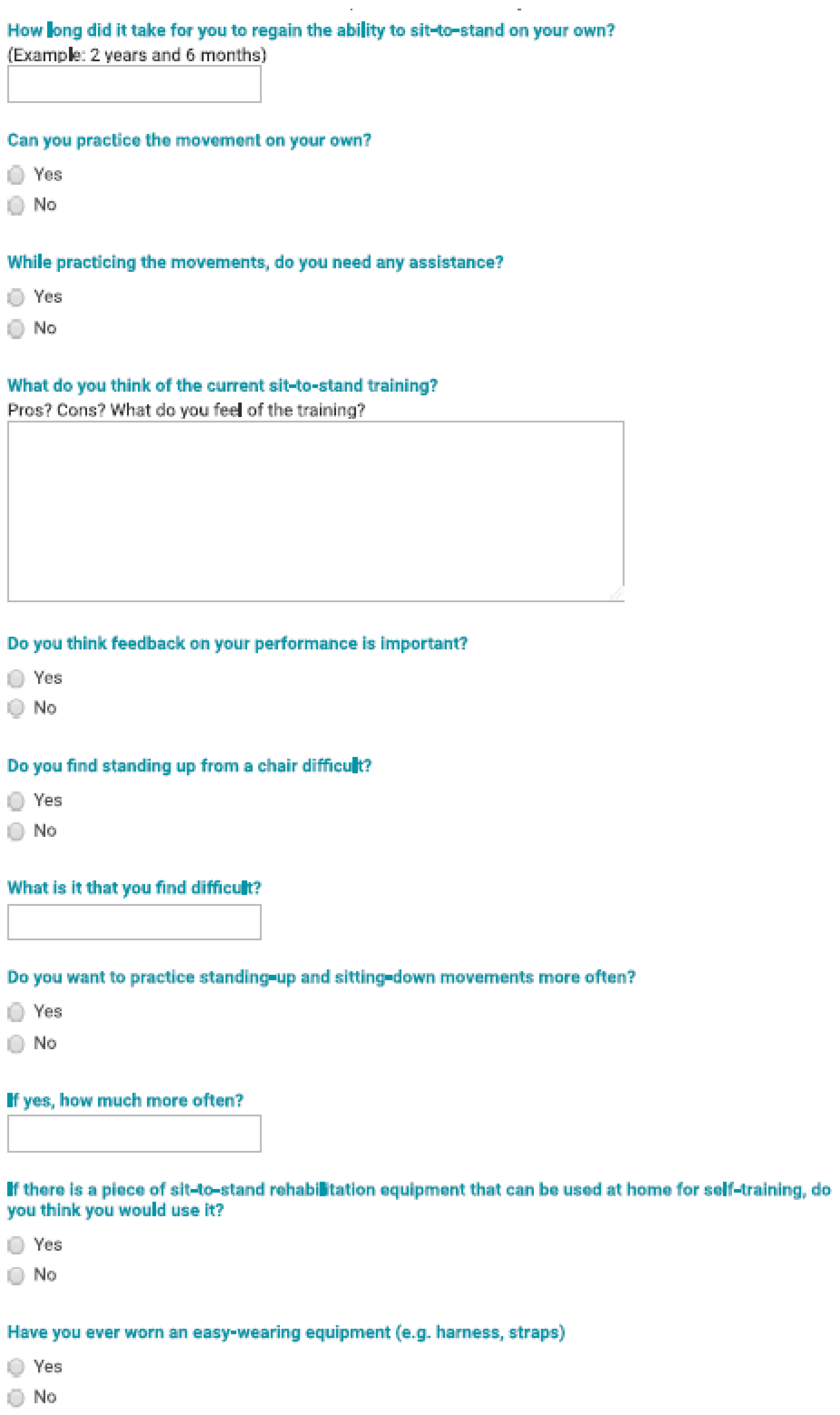
How long is a typical session?
(Example: 1 hour and 30 minutes)

How much time do you spend on practicing standing-up and sitting-down movements?
(Example: 1 hour and 30 minutes)

Are you able to stand from sitting on your own?

- ○ Yes
- ○ No

Appendix 2.2 – Questionnaire for Healthcare Professionals



How long did it take for you to regain the ability to sit-to-stand on your own?
(Example: 2 years and 6 months)

Can you practice the movement on your own?

○ Yes
○ No

While practicing the movements, do you need any assistance?

○ Yes
○ No

What do you think of the current sit-to-stand training?
Pros? Cons? What do you feel of the training?

Do you think feedback on your performance is important?

○ Yes
○ No

Do you find standing up from a chair difficult?

○ Yes
○ No

What is it that you find difficult?

Do you want to practice standing-up and sitting-down movements more often?

○ Yes
○ No

If yes, how much more often?

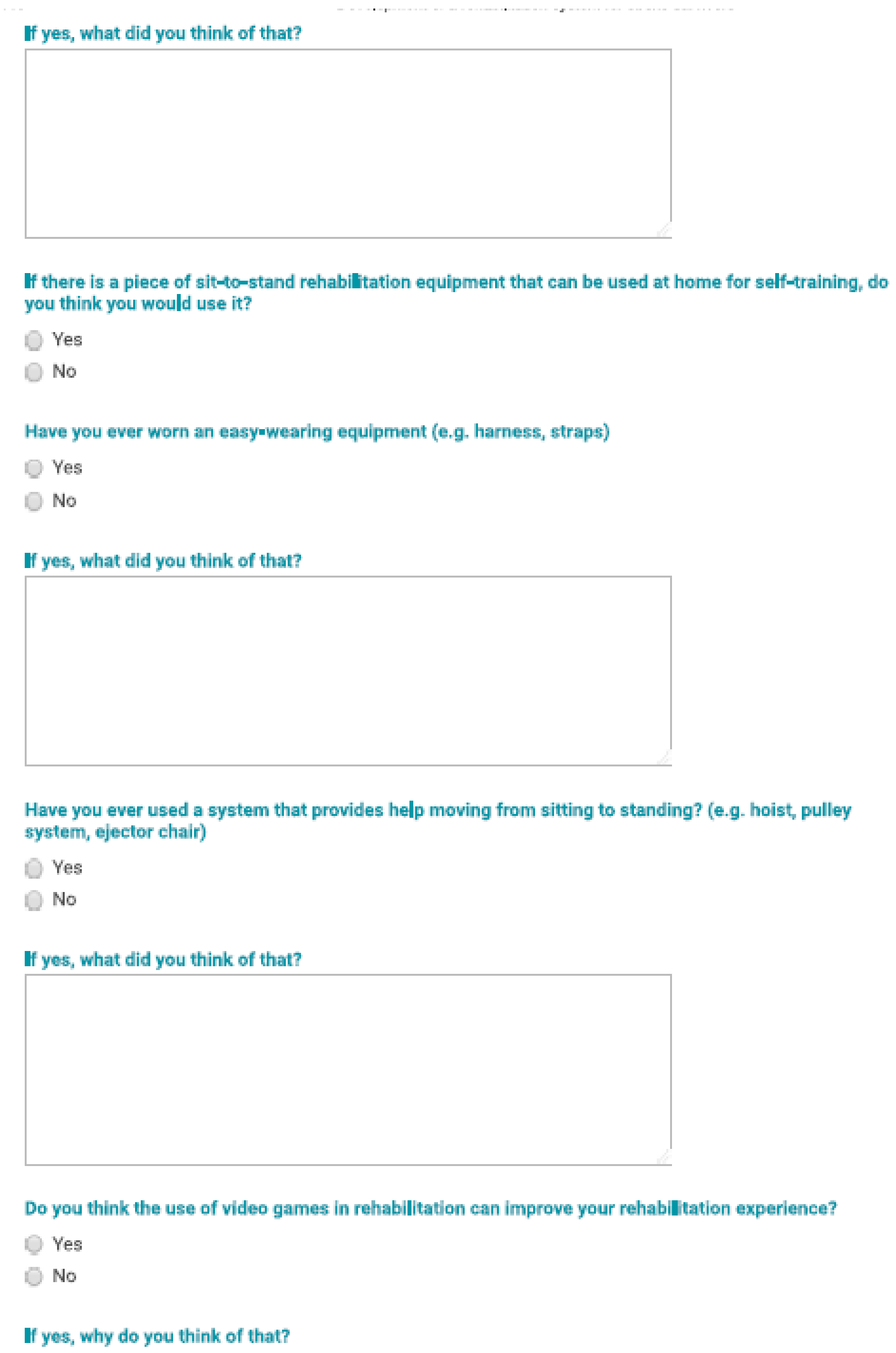
If there is a piece of sit-to-stand rehabilitation equipment that can be used at home for self-training, do you think you would use it?

○ Yes
○ No

Have you ever worn an easy-wearing equipment (e.g. harness, straps)

○ Yes
○ No

Appendix 2.2 – Questionnaire for Healthcare Professionals



If yes, what did you think of that?

If there is a piece of sit-to-stand rehabilitation equipment that can be used at home for self-training, do you think you would use it?

○ Yes

○ No

Have you ever worn an easy-wearing equipment (e.g. harness, straps)

○ Yes

○ No

If yes, what did you think of that?

Have you ever used a system that provides help moving from sitting to standing? (e.g. hoist, pulley system, ejector chair)

○ Yes

○ No

If yes, what did you think of that?

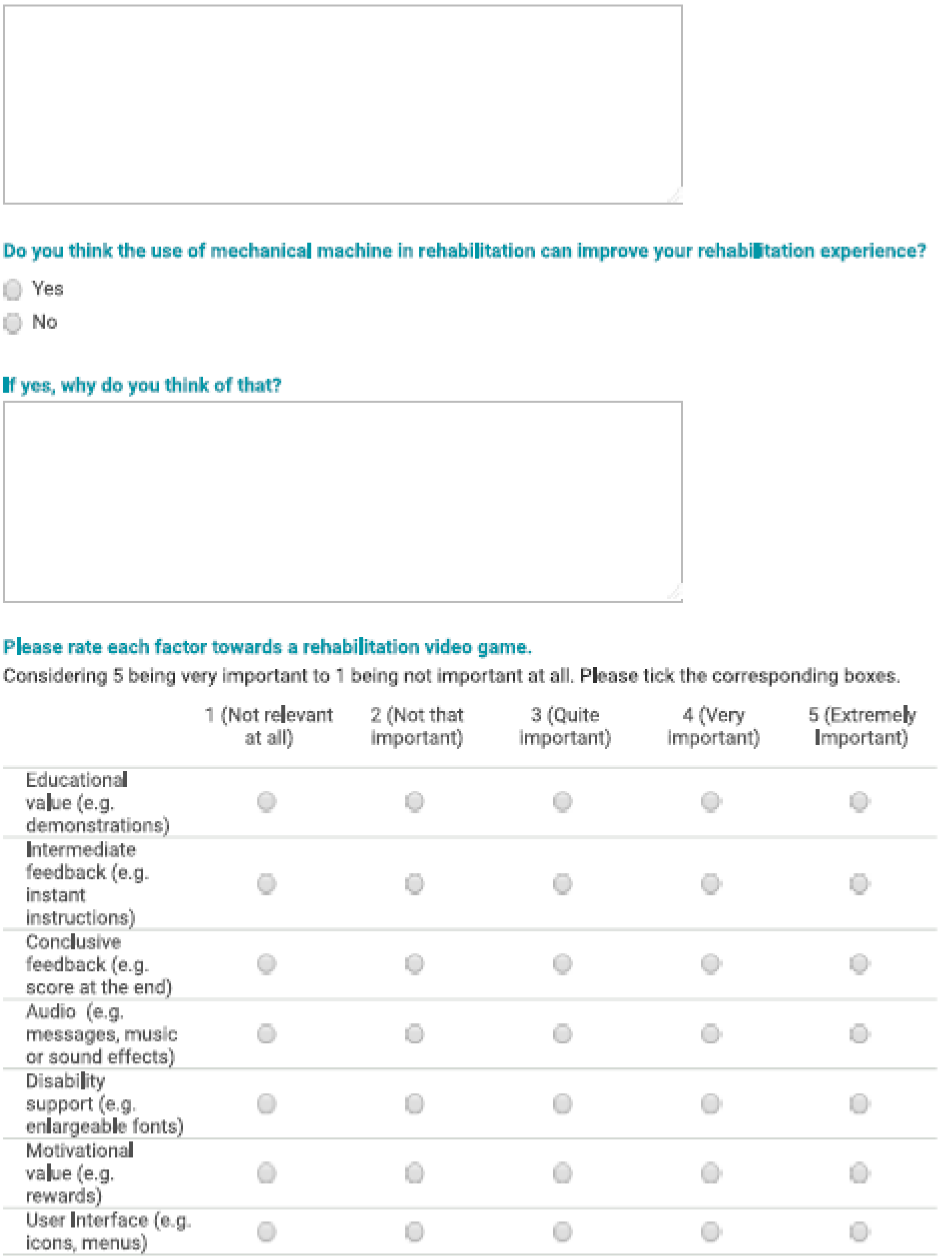
Do you think the use of video games in rehabilitation can improve your rehabilitation experience?

○ Yes

○ No

If yes, why do you think of that?

Appendix 2.2 – Questionnaire for Healthcare Professionals



Do you think the use of mechanical machine in rehabilitation can improve your rehabilitation experience?

○ Yes

○ No

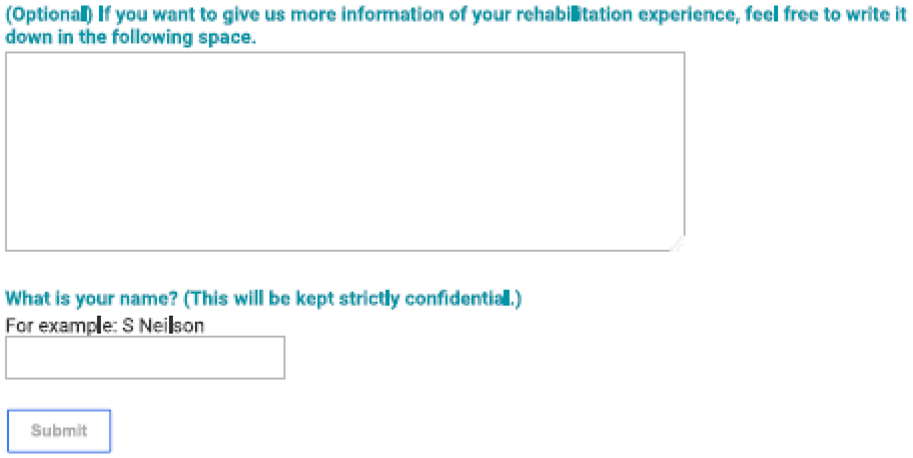
If yes, why do you think of that?

Please rate each factor towards a rehabilitation video game.

Considering 5 being very important to 1 being not important at all. Please tick the corresponding boxes.

	1 (Not relevant at all)	2 (Not that important)	3 (Quite important)	4 (Very important)	5 (Extremely Important)
Educational value (e.g. demonstrations)	○	○	○	○	○
Intermediate feedback (e.g. instant instructions)	○	○	○	○	○
Conclusive feedback (e.g. score at the end)	○	○	○	○	○
Audio (e.g. messages, music or sound effects)	○	○	○	○	○
Disability support (e.g. enlargeable fonts)	○	○	○	○	○
Motivational value (e.g. rewards)	○	○	○	○	○
User Interface (e.g. icons, menus)	○	○	○	○	○

Appendix 2.2 – Questionnaire for Healthcare Professionals



(Optional) If you want to give us more information of your rehabilitation experience, feel free to write it down in the following space.

What is your name? (This will be kept strictly confidential.)

For example: S Neilson

Appendix 3.1 - Product Design Specification

Product Design Specification

This product design specification is a document that defines what the non-yet-designed sit-to-stand (STS) feedback rehabilitation system should intend to achieve. This document contains statements to ensure the subsequent design of the feedback system meets the needs of the users and stakeholders (as captured during the UCD process).

This document shall be revised constantly even after the system has been completed when new knowledge or requirements are learnt.

Contents

Appendix 3.1 - Product Design Specification

- The overall sit-to-stand feedback rehabilitation system shall be referred to as the “system”
- Patients, who will practice STS movements using the system, shall be referred to as the “users”. The users can interact with the system with minimal or no help from any assistance. This would depend on their level of mobility
- Healthcare professionals (e.g. physiotherapists, carers, nurses), who are going to manipulate and control the system either by pre-programmed control or by direct control, shall be referred to as the “operators”. Ideally, the system does not an operator, unless the user mobility is limited

1. Performance and functionality

The feedback system must detect user’s biomechanics motions (e.g. trajectories, balance and weight shift). The gathered and calculated biomechanical data will be analysed. Visual and auditory feedback will be provided to users and operators based on this information.

Motion Detection and Analysis

1.1.1 Hardware, which to be incorporated into the system, must accurately measure the sit-to-stand motions (e.g. refresh rate, sensing range and precision)
1.1.2 The system must be able to analyse user’s STS performance
1.1.3 The system must be able to predict user’s intention of motion by analysing previous motion patterns

Visual Feedback System

The visual feedback system will be virtual reality based and mimick a real-life scenario. The virtual reality system should consist of STS training programs. Computer-assisted visual and auditory feedback must be provided. These programs aim for regaining STS in older adults by allowing users to practice the movement without the supervision of healthcare staff, when necessary. This would reduce the workload of healthcare staff.

1.2.1 A display device to be incorporated into the system for electronic visual display
1.2.2 An audio device to be included. This to allow sound effects and auditory messages to be broadcasted to users
1.2.3 A hardware input peripheral, which to be manipulated by the user, for controlling the training programs (e.g. begin, stop, pause) shall be suitable for users with different types of disability (e.g. blindness, poor fingers coordination)
1.2.4 The virtual reality system must motivate and encourage user
1.2.5 The virtual reality system must be based on a user-friendly interface by allowing effective control operations to be achieved by users of all kinds of disability (e.g. blindness, perception issues)
1.2.6 The use of texts shall be avoided as possible and replaces by graphics (e.g. graphs, icons, pictures)
1.2.7 Texts to be shown must be readable (e.g. enlargeable) for users with visual impairment
1.2.8 Texts on screen shall be repeated in audio for users with severe impairments
1.2.9 All developed hardware must have good usability (ease of use) and high learnability (easy to learn by users of all levels of computer literacy)
1.2.10 The virtual reality system must educate users on ideal STS transfer (e.g. gestures, movements, co-ordination) and provide an appropriate learning experience to all users
1.2.11 Bio-feedback on performance to be provided during training (real-time) and at the end of sessions (interval/conclusive)
1.2.12 All feedback should match with the sequence of an STS transfer (e.g. corresponds to stages of STS) to reduce confusion
1.2.13 The feedback data must be useful for patients and healthcare staff in improving sit-to-stand performance
1.2.14 All feedback and messages must avoid judging users and causing negative feelings (e.g. provide sad faces, give a fail grade)
1.2.15 Feedback should gradually be reduced. This would enable user’s own error detection mechanism to kick-in.
1.2.16 Clear goals (e.g. time, repetitions and balance) must be provided

1.2.17 The virtual reality system must provide the right intensity (e.g. practising time, repetitions, breaks) of therapy for all users

1.2.18 The STS performance will be recorded; therefore, physiotherapists and healthcare staffs are able to monitor patients’ progress and provide more information in setting patient goals and planning therapeutic activities

2. Environment

2.1 The system shall be used indoors in a clinical setting with/without the presence of a healthcare staff or in a home environment

2.2 The system must operate on a flat surface

2.3 Operation temperature: 13°C (56°F) and 30°C (86°F) (According to HSE, British government)

2.4 Noise: Maximum noise rating is 40dB at 1 meter (According to the World Health Organisation)

2.5 The system should be able to operate at standard atmospheric pressure (101,325Pa)

2.6 All electronic components to be protected by plastic casings (from static electricity)

2.7 The system shall be designed to avert the ingress of dirt and dust

3. Safety

3.1 The system must not cause any injury to the users and operators

3.2 The system must provide self-monitoring

3.3 Emergency stop buttons must be reachable by users and operators at all time

3.4 An easy-wearing safety equipment, which must be wore by the user when training, to be fabricated

3.5 Safety supports (e.g. rails, bars, knee supports, arm supports) to be included, if needed

3.6 No shape edges will be exposed

4. Customers

4.1 The primary customers will be patients who have limited STS performance. Sufferers of different neurological diseases, users of prosthetics or orthotics and older adults are all suitable.

5. Ergonomics

5.1 The system must fit (height and weight) for the 5th percentile (Scottish female) and the 95th percentile (Scottish male)

5.2 The system operation should not unduly fatigue the user and/or operator

5.3 All switches must be indicated with different colours or shapes for easy recognition

5.4 The system must have an attractive appearance and be eye-catching

5.5 The image of the system must present reliability, robustness and compactness

5.6 The system power supply shall come from the mains (230V, 50Hz in the U.K.). Nonetheless, the mobile components shall be powered by Universal Serial Bus ports or batteries

5.7 The system must be energy efficient and conserve energy when in static mode

5.8 The sensors which could be attached on users with fitting equipment must not present a feeling of being restrained

6. Size

6.1 The size of the fully assembled system must be kept to a minimum and fit on a standard office desk (150cm by 120cm)

7. Weight

7.1 The weight of the system should be kept to a minimum but enough strength to withstand the weight of the 95th percentile (male)

8. Material

8.1 In order to minimise the cost and time for development, commercially available components and materials will be employed when possible

8.2 The chosen materials must withstand the necessary environmental conditions (See Section 2-Environment)

8.3 The chosen materials and components are to be resistant / not react to water, cleaning liquid, disinfectants and any kinds of chemicals and substances which it might encounter in its working environment

8.4 The chosen materials must not oxidise or corrode within the product life span

8.5 The chosen materials should be able to resist general wear and tear

8.6 The chosen materials should not react with sensitive skin

9. Installation

9.1 The system shall be assembled and disassembled easily for the benefits of portability and transportation

10. Disposal

10.1 Follows the UK's "Waste Electric and Electronic Equipment (WEEE) Regulations 2013", which transpose the "Directive 2012/19/EU" published by the European Union for collection, recycling and recovery of electronic waste

11. Testing

11.1 The system to be easily tested by repair engineers

11.2 The system shall be serviced by a qualified engineer every year

12. Target Cost

12.1 The Cost of the system must be kept as low as possible and be competitive with competitors

12.2 The maximum cost of the overall system should be around GBP£5000

13. Shipping

13.1 The system shall be able to ship across the world by air, road, rail and water in an undefined limit of time

14. Packing

14.1 Cost, size and weight of packaging must be kept to a minimum
14.2 Must be packaged in recyclable materials
14.3 Must be waterproof and prevent corrosion
14.4 Must be easily removed by the installer
14.5 Instructions for fitting and assembly must be included
14.6 Should prevent damage by shock loading

15. Shelf storage life

15.1 There will be no limitation on shelf life as the system will be non-perishable

16. Manufacturing facility

16.1 No constraints and have not been considered yet

17. Life in service

17.1 The system's life in service should be as long as possible; therefore, the initial investment can be recovered
17.2 The system shall work for at least 20 years (8 hours a day)

18. Maintenance

18.1 The system should be completely maintenance free except for cleaning or removing dust from the internal part of the system (e.g. inside a computer)
18.2 Pre-programmed routines can be carried out by operators
18.3 The system must be accessible for repairs

18.4 Disinfection and sterilisation to be achieved frequently (after each use) for hygiene purposes

18.5 The system shall be serviced annually

19. Product lifespan

19.1 The system should have a product life as long as possible; therefore, the initial investment can be recovered

Appendix 3.2 – Function Tree

Appendix 3.3 – Morphological Chart (2)

Appendix 3.4 Generated Concepts

Appendix 3.4 Generated Concepts

Appendix 3.5 – Force-fitting

1. Bubble wand

This object has 4 components:

- Cylinder Tube
    - Red,
    - Hard plastic, smooth, shiny, transparent for volume indication as the bubble solution inside the tube is clearly visible from the outside
    - Can be opened at one end, allowing access to bubble solution
    - Storage device for the bubble solution
    - Can be incorporated with a bubble wand
    - **Using colour metrics to represent feedback (KP), fill up the bar for having high scores, similar to filling up the cylinder tube with bubble solution**

- Bubble wand
    - Red
    - Heart-shaped tip with a hollow, can be hold firmly by two fingers
    - Five circular shaped discs contacting the opening end of the cylinder tube to prevent leakage
    - A long beam connecting a triangular shaped hollow. Users can blow toward the hollow and air particles would flow through the hollow to create bubbles

- Soap Bubbles
    - Hollow spheres enclosing air with layers of soap film
    - Reflective
    - Colours of the objects reflected on the soap film were changed (more colourful, RGB)
    - Images reflected are enlarged

    - **While providing STS feedback (KR) to users, circular bubbles would appear and indicate number of achieved executions (vary in colours and zoom in to catch attention)**

- Soap Solution
    - Water-like viscosity
    - Smells like shampoo
    - Bubbles can be created by shaking/mixing/blowing the solution

2. Staple remover

This object has 2 components:

- Mechanical pivots
    - Two pivot pairs of steep wedges connected to a spring
    - Two sets of parallel spikes can be inserted under the main body of the staple by pressing the remover's hand grips
    - The spring returns the remover to its original open position after use
    - Force (by two fingers) must be applied to maintain the closing position
    - **The opening / closing structure can be used to adjust the harness for position the inertial sensor**

- Hand grips
    - Hard plastic, firm, semi- transparent
    - Trough on each grip, helps to position the fingers

3. CD case

- Soft, semi-rigid plastic structure can hold one CD at a time
- The material is transparent, so the CD is visible, and userd can indicate the disc they wanted
- Protect the CD from scratches and exposure damage (e.g. insulation from water)

- Can be opened and folded, the folding position is held by a circular hub of teeth which grip the disc by its holes and securing the disc and the case
- The structure cannot be folded to reduce its size
- **When providing feedback to users, only provide one type of feedback at a time to reduce the chance of confusion**

4. Green ladybird toy car

- Hard plastic, in the shape of a ladybird (in green)
- It has three wheels under the structure (not visible from top view)
- **Virtual reality based in on a public transport vehicle**
- The car has two main components, first is the ladybird shell, second is the bottom case of the car, attached with 2 Philips screws

5. Bracelet

- Intended to be worn around the wrist or forearm
- Made from loose plastic beads (bluish, circular, mobile and rotate) with a hole in the middle and connected by an elastic band through the hole.
- Easy to wear due to the beads, slip
- **Produce a circular map, like a bracelet, to indicate the number of successful STS**

6. Clothes Peg

- Pink, hard but flexible plastic
- Fastener used to hang up clothes for drying in dry, sunny weather
- Maintain position of clothes on hangers
- A small spring is in the middle
- Due to lever action, when two prongs are pinched at the top of the peg, the prongs could open up. When released, the spring draws and the two prongs shut, hence gripping.
- It has two holes to fit clothes/hangers with different sizes

- **Dry and Sunny weather in VR (provide positive emotions)**
- **Spring is not fixed, can be removed by accident**

7. Cleaning Sponge

- Soft, light, liquid absorbent
- All 4 sides could be used
- Porous
- Return to original position after removing applied pressure
- **Crete a mini game where users sit on a sponge and must move forward/backward/upward/downward to balance.**

Appendix 3.6 – SCAMPER

- Substitute
  - The purpose of displaying a VR environment is to provide everyday-life visual stimuli to users. Other settings can be substituted. Especially settings which require is moving, unpredictable (e.g. people around, obstacles) STS motion. E.g. public transport
  - Substitute graphical indications of performance instead of texts
- Combine
  - Combine visual feedback plus verbal instructions
  - Combine avatar with bar/graphs/metric tools for delivering feedback
- Adapt
  - Using graphs to represent qualitative feedback could be difficult. Use colour metric
  - Toolbar in operation systems (windows, apple, android) to display results, e.g. balance score, time, stage of STS
- Modify (Max, Min)
  - Maximise a particular body part, which should be activated during a particular STS phase
  - Introduce different types of graphs to represent feedback (Knowledge of performance), rather than just one
  - Avatar shows 2 different orientations. Therefore, it would be easier to tell upward/downward, left/right and balance of the user
  - Max feedback in texts for visual impairments
- Put to other use
  - Avatar in different orientations shall not only used to provide demonstration, but also feedback
- Eliminate

Appendix 3.6 – SCAMPER

  - In order to focus user attention to the STS movement, which is a complex task and requires the activation/control/coordination of many muscles from toes to head, remove non-essential real-time feedback, for example graphs, excessive quantitative and/or qualitative feedback. Leave concept with avatar for visual cues and add auditory qualitative feedback (e.g. Well done, Excellent) and instructions (e.g. move your arms forward). Do not graph for magnitude of errors.

- Rearrange (Reverse)
  - Rearrange the position of the avatar and verbal instruction on screen for better visual effects and easy explanations (Texts should match with user’s movements)

Appendix 4.1 – Inertial Sensor's specifications

Phidgets

PHIDGETS Inc.
Unit 1 - 6115 4 St SE Calgary AB T2H 2H9 Canada +1 403 282-7335

PhidgetSpatial 3/3/3 Basic

ID: 1042_0B

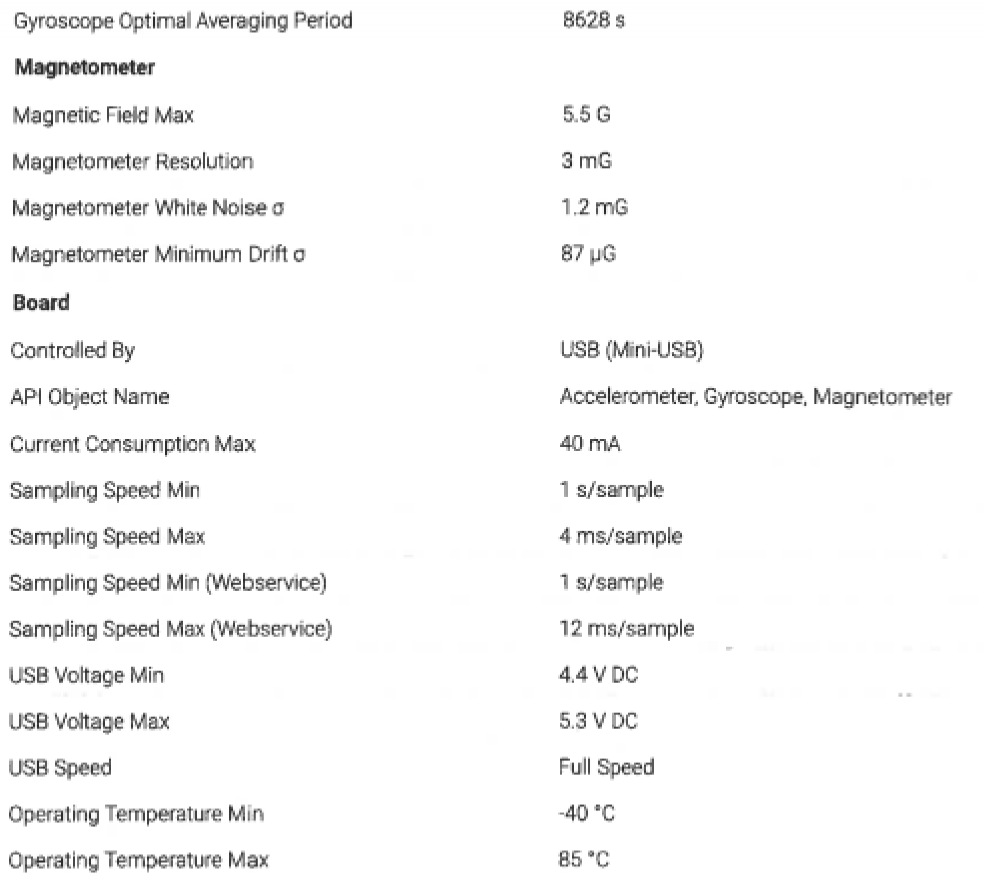
This spatial board has a 3-axis accelerometer, gyroscope and compass and connects to your computer via USB.

Description Connection & Compatibility User Guide Specifications API Resources Other Spatials

Product Specifications

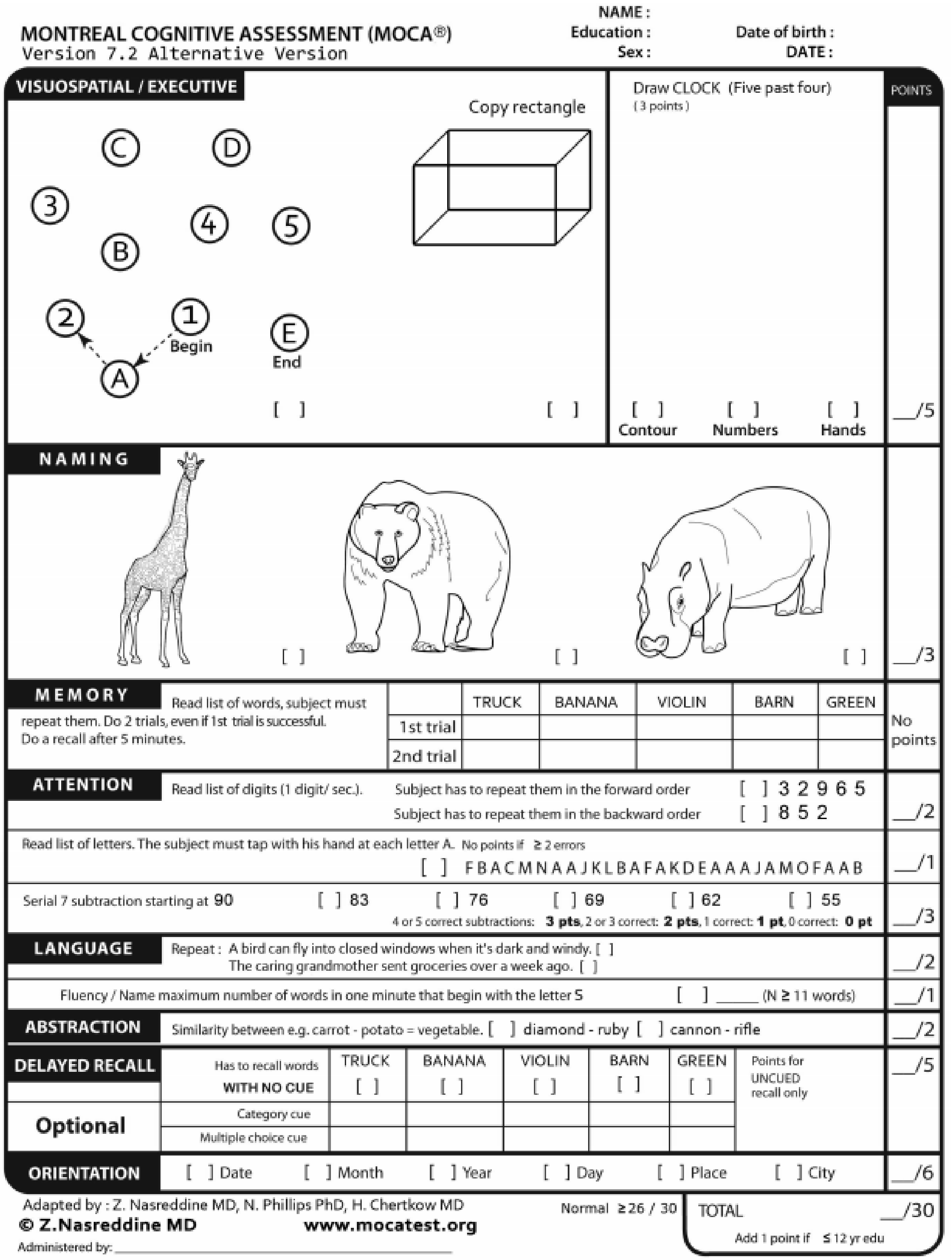
Accelerometer	
Acceleration Measurement Max	± 8 g
Acceleration Measurement Resolution	976.7 µg
Accelerometer White Noise σ	2.8 mg
Accelerometer Minimum Drift σ	1.9 mg
Accelerometer Optimal Averaging Period	286 s
Gyroscope	
Gyroscope Speed Max	± 2000°/s
Gyroscope Resolution	0.07°/s
Gyroscope White Noise σ	0.59°/s
Gryoscope Minimum Drift σ	0.0019°/s

Appendix 4.1 – Inertial Sensor’s specifications



Gyroscope Optimal Averaging Period	8628 s
Magnetometer	
Magnetic Field Max	5.5 G
Magnetometer Resolution	3 mG
Magnetometer White Noise σ	1.2 mG
Magnetometer Minimum Drift σ	87 μG
Board	
Controlled By	USB (Mini-USB)
API Object Name	Accelerometer, Gyroscope, Magnetometer
Current Consumption Max	40 mA
Sampling Speed Min	1 s/sample
Sampling Speed Max	4 ms/sample
Sampling Speed Min (Webservice)	1 s/sample
Sampling Speed Max (Webservice)	12 ms/sample
USB Voltage Min	4.4 V DC
USB Voltage Max	5.3 V DC
USB Speed	Full Speed
Operating Temperature Min	-40 °C
Operating Temperature Max	85 °C

Appendix 6.1 – Montreal Cognitive Assessment



MONTREAL COGNITIVE ASSESSMENT (MOCA®)
Version 7.2 Alternative Version

NAME :
Education : **Date of birth :**
Sex : **DATE :**

VISUOSPATIAL / EXECUTIVE

[ ]

Copy rectangle [ ]

Draw CLOCK (Five past four) (3 points)

[ ] Contour [ ] Numbers [ ] Hands

POINTS __/5

NAMING

[ ] [ ] [ ] __/3

MEMORY Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.

	TRUCK	BANANA	VIOLIN	BARN	GREEN
1st trial					
2nd trial					

No points

ATTENTION Read list of digits (1 digit/ sec.).
Subject has to repeat them in the forward order [ ] 3 2 9 6 5
Subject has to repeat them in the backward order [ ] 8 5 2
__/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors
[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B __/1

Serial 7 subtraction starting at 90 [ ] 83 [ ] 76 [ ] 69 [ ] 62 [ ] 55
4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt** __/3

LANGUAGE Repeat : A bird can fly into closed windows when it's dark and windy. [ ]
The caring grandmother sent groceries over a week ago. [ ] __/2

Fluency / Name maximum number of words in one minute that begin with the letter S [ ] _____ (N ≥ 11 words) __/1

ABSTRACTION Similarity between e.g. carrot - potato = vegetable. [ ] diamond - ruby [ ] cannon - rifle __/2

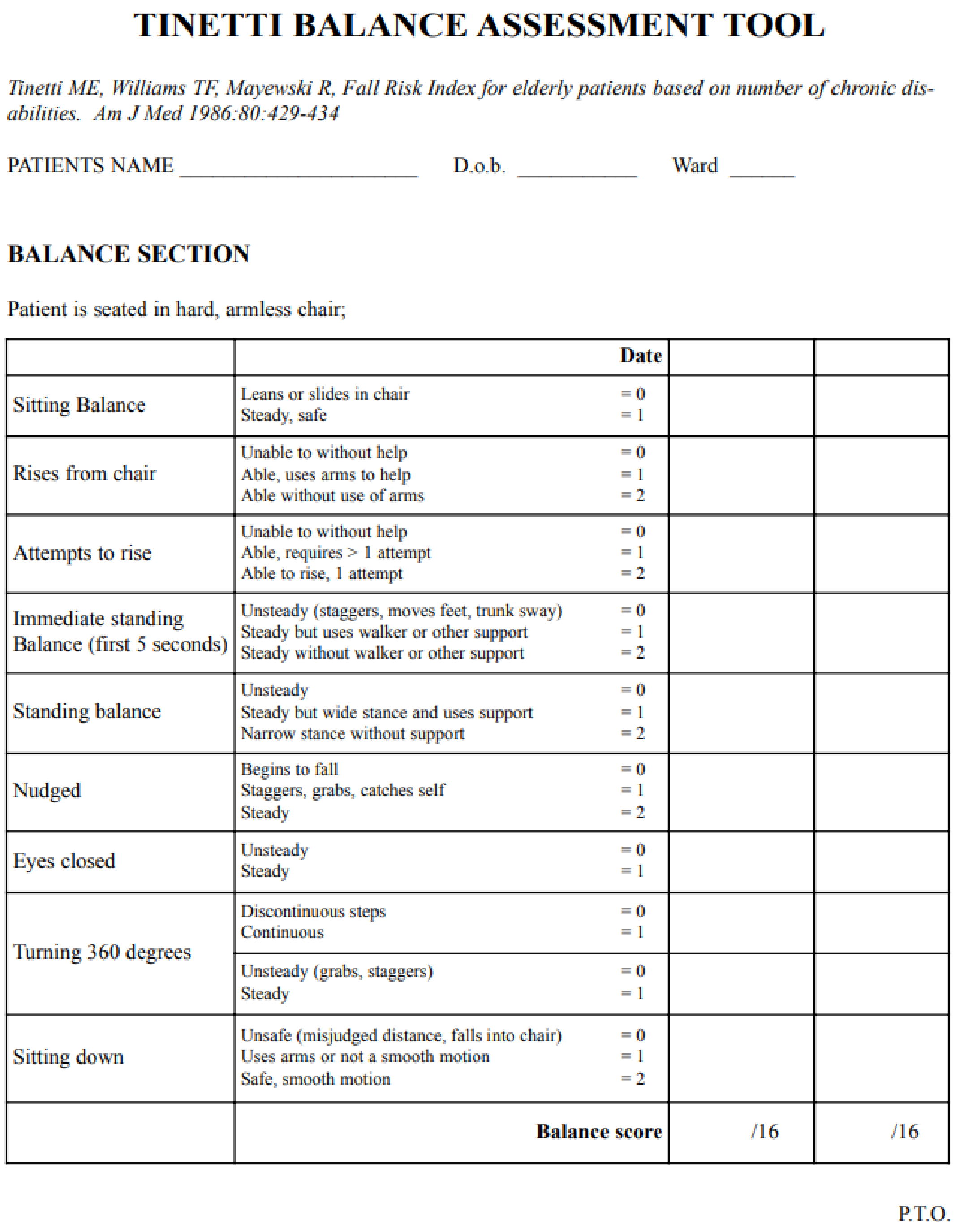
DELAYED RECALL	Has to recall words **WITH NO CUE**	TRUCK [ ]	BANANA [ ]	VIOLIN [ ]	BARN [ ]	GREEN [ ]	Points for UNCUED recall only	__/5
Optional	Category cue							
	Multiple choice cue							

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City __/6

Adapted by : Z. Nasreddine MD, N. Phillips PhD, H. Chertkow MD
© Z.Nasreddine MD **www.mocatest.org**
Administered by: ______________________

Normal ≥26 / 30 TOTAL __/30
Add 1 point if ≤ 12 yr edu

Appendix 6.2 – Tinetti Balance Assessment Tool



TINETTI BALANCE ASSESSMENT TOOL

Tinetti ME, Williams TF, Mayewski R, Fall Risk Index for elderly patients based on number of chronic disabilities. Am J Med 1986:80:429-434

PATIENTS NAME ____________________ D.o.b. __________ Ward _____

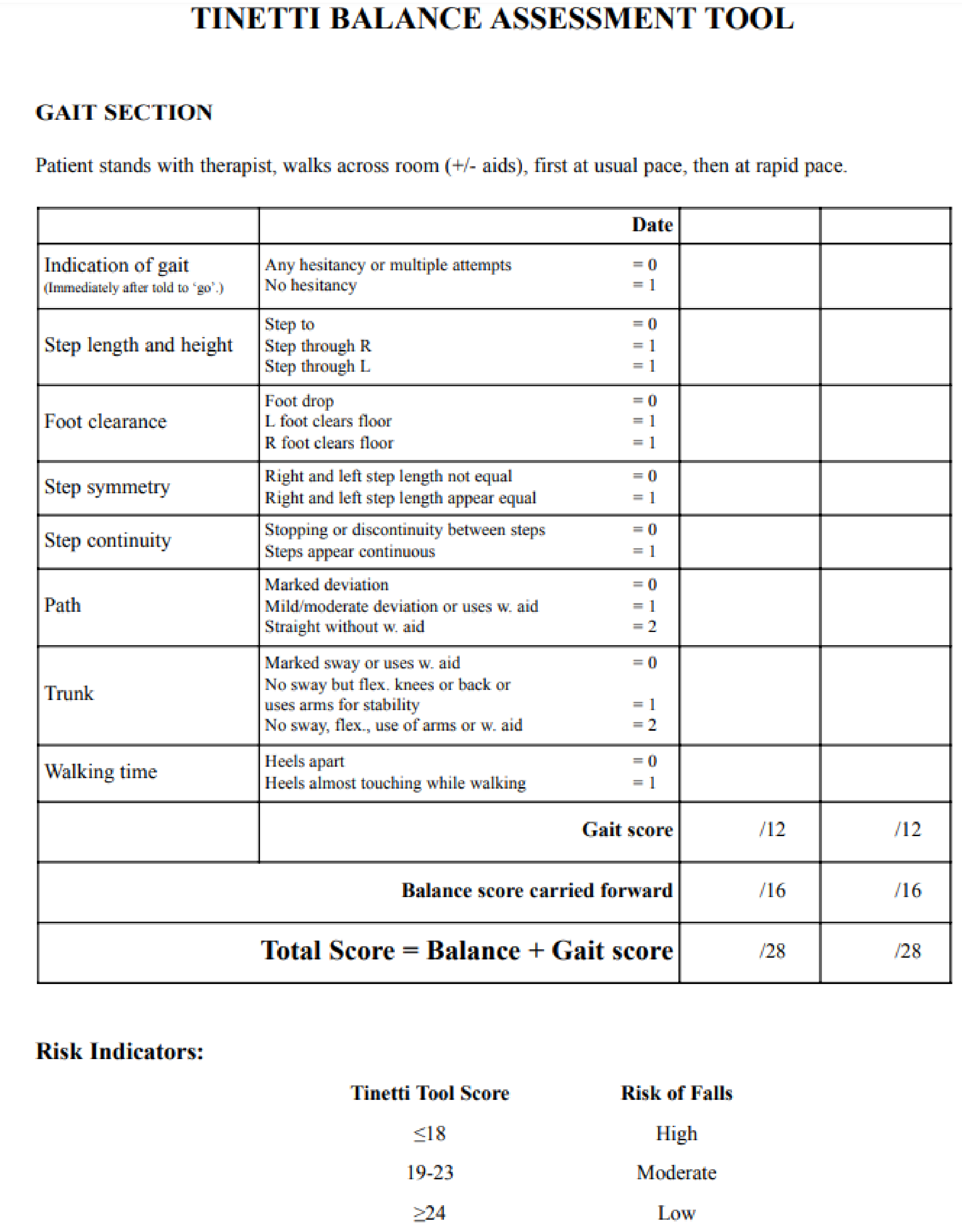
BALANCE SECTION

Patient is seated in hard, armless chair;

	Date		
Sitting Balance	Leans or slides in chair = 0 Steady, safe = 1		
Rises from chair	Unable to without help = 0 Able, uses arms to help = 1 Able without use of arms = 2		
Attempts to rise	Unable to without help = 0 Able, requires > 1 attempt = 1 Able to rise, 1 attempt = 2		
Immediate standing Balance (first 5 seconds)	Unsteady (staggers, moves feet, trunk sway) = 0 Steady but uses walker or other support = 1 Steady without walker or other support = 2		
Standing balance	Unsteady = 0 Steady but wide stance and uses support = 1 Narrow stance without support = 2		
Nudged	Begins to fall = 0 Staggers, grabs, catches self = 1 Steady = 2		
Eyes closed	Unsteady = 0 Steady = 1		
Turning 360 degrees	Discontinuous steps = 0 Continuous = 1		
	Unsteady (grabs, staggers) = 0 Steady = 1		
Sitting down	Unsafe (misjudged distance, falls into chair) = 0 Uses arms or not a smooth motion = 1 Safe, smooth motion = 2		
	Balance score	/16	/16

P.T.O.

Appendix 6.2 – Tinetti Balance Assessment Tool



TINETTI BALANCE ASSESSMENT TOOL

GAIT SECTION

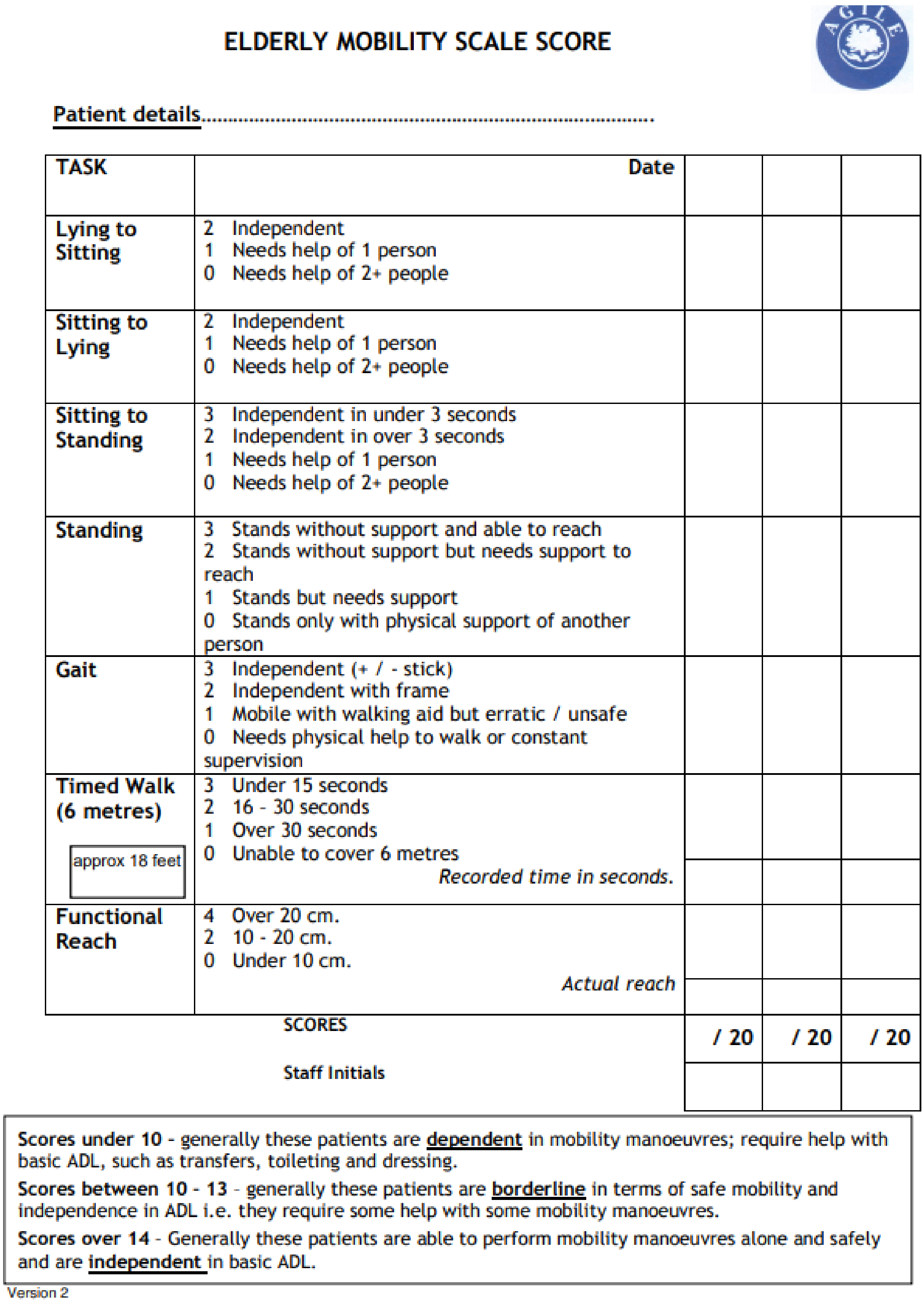
Patient stands with therapist, walks across room (+/- aids), first at usual pace, then at rapid pace.

	Date		
Indication of gait (Immediately after told to 'go'.)	Any hesitancy or multiple attempts = 0 No hesitancy = 1		
Step length and height	Step to = 0 Step through R = 1 Step through L = 1		
Foot clearance	Foot drop = 0 L foot clears floor = 1 R foot clears floor = 1		
Step symmetry	Right and left step length not equal = 0 Right and left step length appear equal = 1		
Step continuity	Stopping or discontinuity between steps = 0 Steps appear continuous = 1		
Path	Marked deviation = 0 Mild/moderate deviation or uses w. aid = 1 Straight without w. aid = 2		
Trunk	Marked sway or uses w. aid = 0 No sway but flex. knees or back or uses arms for stability = 1 No sway, flex., use of arms or w. aid = 2		
Walking time	Heels apart = 0 Heels almost touching while walking = 1		
	Gait score	/12	/12
Balance score carried forward		/16	/16
Total Score = Balance + Gait score		/28	/28

Risk Indicators:

Tinetti Tool Score	**Risk of Falls**
≤18	High
19-23	Moderate
≥24	Low

Appendix 6.3 – Elderly Mobility Scale Score



ELDERLY MOBILITY SCALE SCORE

Patient details...

TASK	**Date**			
Lying to Sitting	2 Independent 1 Needs help of 1 person 0 Needs help of 2+ people			
Sitting to Lying	2 Independent 1 Needs help of 1 person 0 Needs help of 2+ people			
Sitting to Standing	3 Independent in under 3 seconds 2 Independent in over 3 seconds 1 Needs help of 1 person 0 Needs help of 2+ people			
Standing	3 Stands without support and able to reach 2 Stands without support but needs support to reach 1 Stands but needs support 0 Stands only with physical support of another person			
Gait	3 Independent (+ / - stick) 2 Independent with frame 1 Mobile with walking aid but erratic / unsafe 0 Needs physical help to walk or constant supervision			
Timed Walk (6 metres) approx 18 feet	3 Under 15 seconds 2 16 - 30 seconds 1 Over 30 seconds 0 Unable to cover 6 metres			
	Recorded time in seconds.			
Functional Reach	4 Over 20 cm. 2 10 - 20 cm. 0 Under 10 cm.			
	Actual reach			
	SCORES	**/ 20**	**/ 20**	**/ 20**
	Staff Initials			

Scores under 10 - generally these patients are **dependent** in mobility manoeuvres; require help with basic ADL, such as transfers, toileting and dressing.

Scores between 10 - 13 - generally these patients are **borderline** in terms of safe mobility and independence in ADL i.e. they require some help with some mobility manoeuvres.

Scores over 14 - Generally these patients are able to perform mobility manoeuvres alone and safely and are **independent** in basic ADL.

Version 2

Appendix 6.4 – System Specifications

All the trials reported in this thesis (chapter 4, 5 and 6) were conducted on a computer with the following hardware and software configurations:

CPU: Intel Core i3 3217U (1.8 GHz)

RAM: 8 GB DDR3 SDRAM 1600 MHz

Graphic Card: Intel HD Graphics 4000

Operating System: Windows 7 Service Pack 1

System Software Package: LabVIEW 2013 Service Pack 1

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