REDUCING COMPENSATORY MOVEMENTS IN STROKE THERAPY THROUGH THE USE OF ROBOTIC DEVICES AND AUGMENTED FEEDBACK

by

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Abstract

Compensatory movements are commonly employed by stroke survivors to adapt to the loss of motor function. However, their long-term use can be detrimental to post-stroke recovery of function. In this work, we focused on trunk displacement, which is a compensatory movement that stroke survivors use when reaching forward. Current therapeutic practices to reduce this tendency rely on the use of physical restraints to secure a person to a chair. An alternate approach to reduce compensation is the use of active technology that delivers augmented feedback about trunk movement. Using this methodology provides several advantages over physical restraints, such as: the person is actively involved in the planning and executing of the movement rather than relying on a physical barrier that continuously prevents trunk movement; the feedback intensity, frequency, and thresholds can easily be modified in real time; the system is less intrusive as it does not require the person to be strapped or secured to a chair by someone else; it can be used safely without direct supervision; the trunk compensation feedback can be used as a variable inside a motivating video game scenario.

This dissertation is comprised of three studies to investigate: the extent of stroke survivors' trunk displacement when reaching forward to targets at different heights (Study 1), the use of visual and force feedback (Study 2), and the importance of including game scores (Study 3) to reduce trunk compensation. The results from these studies suggest that target height influences the degree of trunk compensation of hemiparetic participants. In addition, the use of visual and force feedback to cue participants about their level of trunk compensation can lead to a reduction of this movement. Similarly, the use of game scores resulted in a reduction of trunk compensation. No feedback modality or combination was superior to another for reducing trunk displacement.

The findings from this work suggest that the use of augmented feedback is a viable approach to reduce trunk compensation in hemiparetic stroke survivors. These ideas should be tested in long-term interventions before we can make a final recommendation to the rehabilitation community.

Lay Summary

In our work, we investigated if we could use technology to reduce unwanted trunk movements of people with stroke while they are using their arms, for example. In our experiments, we measured the forward trunk lean of people while they were reaching for an object. We found that providing force (using a robotic device) or visual (using a computer screen) information about unwanted trunk movements can lead to their reduction. In a similar manner, providing point scores to people with stroke who are playing computer games also resulted in a reduction of these movements. We did not find that any type or combination of information was superior to any other. Our results provide support to the idea of using technology to modify the unwanted trunk movements of people with stroke.

Preface

All of the work presented in Chapters 2-4 was conducted in the Robotics for Rehabilitation Exercise and Assessment in Collaborative Healthcare (RREACH) Lab at the University of British Columbia, Vancouver, Canada. All research studies were approved by the University of British Columbia's Clinical Research Ethics Board (certificate number: H14-01485).

A version of Chapter 2 has been published in the Journal of Motor Behavior: B.A. Valdés, S.M.N. Glegg, H.F.M. Van der Loos, "Trunk Compensation during Bimanual Reaching at Different Heights by Healthy and Hemiparetic Adults", Journal of Motor Behavior, Published online: December 9th, 2016, www.tandfonline.com/doi/abs/10.1080/00222895.2016.1241748.

A version of Chapter 3 has been published in the Journal of Archives of Physical Medicine and Rehabilitation: B.A. Valdés, A.N. Schneider, H.F.M. Van der Loos, "Reducing Trunk Compensation in Stroke Survivors: A Randomized Crossover Trial Comparing Visual vs. Force Feedback Modalities", Archives of Physical Medicine and Rehabilitation, Published online: May 17th, 2017, https://doi.org/10.1016/j.apmr.2017.03.034.

A version of Chapter 4 has been submitted for publication: B.A. Valdés, H.F.M. Van der Loos, "Biofeedback vs. Game Scores for Reducing Trunk Compensation after Stroke: A Randomized Crossover Trial".

For the work presented in Chapters 2-4, the author led the studies' designs, systems development, data acquisition and analysis, and writing of the manuscripts. Dr. Machiel Van der

Loos (Chapters 2-4) contributed with ideas to develop the studies' designs, provided ongoing supervision and support, and took part in the writing and editing of the manuscripts. Occupational therapists Stephanie Glegg (Chapter 2) and Andrea Schneider (Chapter 3) evaluated the participants' level of impairment, assisted in the study sessions, and provided a clinical perspective to the writing and editing of the manuscripts.

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List of Symbols

CI	95% Confidence Interval
CV	Coefficient of Variation
d	Cohen's d
IQR_{diff}	Interquartile Range of the Differences
m_{diff}	Median of the Differences
PS	Probability of Superiority
PS_{dep}	Probability of Superiority for Dependent Groups
r_s	Spearman's Correlation Coefficient
SE_{diff}	Standard Error of the Differences
U	Mann-Whitney U value
$\bar{x}_{diff}$	Mean of the Differences

List of Abbreviations

3D	Three Dimensional
ANOVA	Analysis of Variance
ANCOVA	Analysis of Covariance
DOF	Degrees of Freedom
FMA	Fugl-Meyer Assessment
MAS	Modified Ashworth Scale
Q-Q	Quantile-Quantile
ROM	Range of Motion
RMS	Root Mean Square
RMANOVA	Repeated Measures Analysis of Variance
RPS	Reaching Performance Scale
SUS	System Usability Scale
TR	Trunk Restraint
UE	Upper-Extremity
VS	Visual Symmetry

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I would like to thank my family for their continuous support in every stage of my life. Your love and understanding have always given me the courage to take risks and dream big. Thank you for always being there for me.

To my wife Mónica: we did it! Since the day we met, I have been living the most incredible adventure. Everything I have achieved is because of you – I love you…

Esta disertación está dedicada a mi esposa Mónica

Chapter 1: Introduction

For stroke survivors, the use of compensatory movements can be detrimental for upper extremity motor recovery [1], especially for those with hemiparesis. A common compensatory movement present during upper limb reaching is trunk displacement [2]. However, few strategies for reducing this movement have been considered. Current therapeutic practices rely on the use of physical restraints (straps and/or harnesses) to secure a person to the back of a chair [3], which are not ideal for unsupervised rehabilitation and only passively prevent trunk movement. As a result, there is a current need for alternate methods that promote the use of correct movement patterns both in the clinic and in the home. In this sense, technology can act as an enabler to create new ways of reducing trunk compensation. Still, there is a gap in the literature as trunk compensation has only been investigated as a secondary theme in robotic and computer-aided rehabilitation.

The overall goal of this dissertation was to investigate the reduction of stroke survivors' trunk compensation through the use of augmented feedback provided by robotic devices and commercially available technology. By studying the use of technology for reducing these unwanted movements, we aimed to provide supporting evidence for the use of alternate methods that focus on the provision of feedback and the quantitative evaluation of stroke survivors' reaching movements.

The following chapter presents an overview of the literature on the topics of stroke rehabilitation, compensatory movements, and the use of technology in therapy. In addition, the research questions and objectives of this dissertation are presented at the end of this chapter.

1.1 Stroke

When a vessel that supplies blood to the brain becomes blocked or ruptures, neurological and physical functions can be affected by the resulting infarct. Every year approximately 15 million people worldwide suffer a stroke and of these, 5 million are left permanently disabled [4]. The majority of stroke survivors return home after only a few weeks of receiving physical therapy, which in turn forces them to rely on external clinics to continue rehabilitating. However, the high cost per session acts as a disincentive to continue therapy, as public health systems rarely cover the entirety of these expenses. A possible alternative is complementing the limited number of visits to the clinics with prescribed home therapy. However, the repetitive and monotonous nature of prescribed home therapy tends to discourage patients from continuing in these programs. Even for those who do continue, the fact that this therapy is unsupervised can lead to the practice and learning of non-optimal movements. As a result, there is a need for unsupervised rehabilitation programs that promote correct movement patterns and provide motivating, meaningful repetitive training.

1.1.1 Hemiparesis

The most common physical impairment after suffering a stroke is hemiparesis, a general weakness on one side of the body that affects the ability of people to move their upper and lower extremities. This occurs as a result of neurological damage to areas of the brain that control the motor functions of the body. While most stroke survivors regain enough leg function to walk again, only 5% to 20% show complete functional recovery of their paretic arm and hand [5]. Consequently, millions of people around the world have to live with a disabled upper extremity,

a condition that affects their ability to perform everyday activities and live an independent life. As a result, this dissertation focused on upper limb physical rehabilitation.

1.1.2 Bimanual Therapy

Older adults (high risk of stroke) tend to use both hands at the same time for most of their daily activities [6]. Therefore, it is crucial to include therapy exercises that involve interlimb co-ordination, if we want stroke survivors to regain their lost bimanual abilities. Furthermore, there is evidence that practicing bimanual movements leads to the coupling of homologous muscles in both limbs, which promotes the activation of both cerebral hemispheres [7]. The reduction of inhibition on the affected hemisphere in bimanual movements and the neural information coming from the unaffected hemisphere could be exploited to guide and increase the motor output of the affected limb [8]. Moreover, it has been shown that in healthy individuals, bimanual training can lead to improvements in unimanual performance [9], which could help to transfer bimanual movement gains to everyday functional gains. Consequently, the practice of bimanual motions should be encouraged to relearn the lost bimanual capacities, and thus this dissertation focused on a bimanual approach to achieve this goal.

1.2 Compensatory Movements

Motor compensation can be defined as: '…the appearance of new motor patterns resulting from the adaptation of remaining motor elements or substitution, meaning that functions are taken over, replaced, or substituted by different end effectors or body segments' [1, p.315]. People with hemiparesis tend to compensate for lost function by taking advantage of the redundant degrees of freedom of their body. For example, using shoulder hike to compensate for lack of

elbow flexion when lifting their arm, or using the unaffected hand to complete tasks that would normally involve the affected side. By using these compensatory motion strategies, the person manages to maintain the ability to interact with the surrounding environment. However, in general, compensatory movements are considered to be maladaptive and difficult to unlearn and thus should be avoided [10]. Moreover, they could lead to orthopaedic problems, reinforce distorted joint positions, and produce muscle shortening [2]. Compensatory movements can also lead to a pattern of "learned non-use" [11], in which the person continually avoids using the joints on the affected side, which eventually leads to a further decrement of the joints' capacity to move.

A common compensatory movement when reaching [2] and orienting the hands for grasping [12] is anterior trunk displacement, which is used by stroke survivors to compensate for the lack or reduction of elbow extension and shoulder flexion. Due to its prevalence and negative effects, trunk displacement is identified as one of the most important compensatory movements to reduce in therapy [13]. Although a healthy forward-reaching movement does involve some trunk displacement, the magnitude of displacement is more than 4.5 times greater in stroke survivors [14]. Moreover, stroke survivors tend to use trunk displacement even when the target is well within arm's reach [15]. As a result of the ubiquitous presence of trunk displacement in reaching patterns of stroke survivors, a reduction of this movement could be used to characterize "true" motor recovery at the body function/structure level [1] and serve as an assessment metric of the survivors' progress in unsupervised therapy.

1.2.1 Trunk Restraint

At the moment, the most widely used strategy for reducing trunk displacement is trunk restraint (TR) [14]. When this strategy is employed, a therapist straps the patient to the back of a chair, using a custom-built harness, to hold the trunk in an upright position as the person performs different reaching activities. Using TR in therapy has shown that limiting trunk involvement promotes the use of ranges of motions that are not usually recruited in unrestrained reaching. In a study in which subjects in two groups (TR, no TR) performed reaching exercises [16], unrestricted movement kinematics were recorded for both groups before, immediately after, and 24 hours after the training. The TR group showed greater gains in elbow extension, a greater decrease in trunk involvement, and improved temporal interjoint coordination. These improvements were maintained after 24 hours. In a randomized controlled trial [10] of a five-week, therapist-supervised home program it was found that in more severely affected patients, TR increased elbow extension and decreased trunk movement after a 1-month follow-up; the opposite effect was observed in the control group (without TR). The results from these studies suggest that using TR in therapy forces survivors to use larger joint ranges of motion than they use in unconstrained reaching. Thus, it seems that premorbid movement patterns may not be completely lost after stroke, but that they remain masked by the use of alternate compensatory strategies.

1.2.2 Disadvantages of Trunk Restraint

TR therapy is not ideal for unsupervised therapy, as it requires the patient to be physically constrained to a chair and a therapist to oversee the exercises. In addition, the use of trunk restraints only passively prevents the occurrence of trunk displacement, and does not necessarily

mean that the person is making a cognitive decision to reduce this movement [17]. As a result, these physical restraints might prevent the patient from actively planning/programming their trunk movements, which could inhibit important efferent and afferent information necessary for creating the internal models of the movements [18].

The feedback the person receives is merely a physical constraint that prevents them from moving, which is continuously activated and precludes the opportunity to measure progress and change the level of restraint. Moreover, varying the frequency at which this information is given could also help to prevent the patient's reliance on the feedback itself, making it more likely that improvements be maintained when the feedback is removed [19]. The negative effects that continuous external feedback have on the long-term learning process of motor tasks has been thoroughly investigated in the motor learning literature. That research led to the development of the "Guidance Hypothesis" [20], which states that providing frequent feedback diminishes the capability of a person to learn a motor skill once the feedback is removed. Consequently, based on the guidance hypothesis, the potential negative effects of using trunk restraints for "teaching" stroke survivors could be mitigated by using alternate strategies that focus on the provision of faded feedback. These facts open a new set of possibilities for using computer and robotic technologies instead of trunk restraints for providing extrinsic feedback to stroke survivors about their level of compensation.

One example of using technology to reduce compensation was the system developed by Thielman [17], which used a pressure sensor on the back of a chair to detect trunk compensation while reaching. When subjects moved their trunk away from the chair, feedback was given in the

form of an auditory cue. Two groups (auditory cue and TR), participated in twelve sessions. For the Reaching Performance Scale[1], there were more improvements in the feedback group when reaching in the immediate workspace. Additionally, there were no significant differences in the other impairment and activity measurement scales used in the study, which reinforces the point that this strategy could obtain similar results to using TR. A limitation of this study was the use of a sensor that could only detect whether or not the subject was compensating, but not the magnitude of this compensation, which could be used to shape the exercises progressively and to measure the improvement of the user in unsupervised therapy. Nevertheless, this study provides evidence that using external feedback to reduce compensation seems to be a viable option for substituting or complementing current trunk restraint therapy.

1.3 Technology in Therapy

In the rehabilitation literature, there is evidence that if a person does thousands of repetitions of goal-oriented tasks even if they are in the chronic stage of stroke, they have the capacity to recover some of the lost functions due to the neuroplastic nature of the human brain [21]. However, the number of functional repetitions a stroke survivor does during a typical physical therapy session in North America is approximately 30 [22]. Given that a much higher dose of repetitions is needed to effect actual neuroplastic changes, there is a necessity for new therapy strategies that enable the patient to complete these intense rehabilitation programs even after being released from the hospital. One approach to tackle this problem is to use technology as a

[1] Scale for identifying and quantifying movement patterns and compensation in reach-to-grasp tasks [65].

tool for achieving more repetitions while providing immediate feedback to the users about their movements and results.

Robotic devices have been used in the last few decades [23] to aid therapists by reducing the physical effort and time they have to spend in one-on-one sessions with their clients. These devices have the potential to make rehabilitation more widely available, as more patients can be reached with the same number of staff. Moreover, given the need for high-dosage therapy, we can take advantage of one of the core reasons robots are used in the first place: the repetition of functional tasks. The fact that robotic devices can apply forces to the users' limbs and obtain precise kinematic measures about their movement creates an advantage over conventional therapy; the ability to precisely monitor the patient's motion and modify the applied forces accordingly enables therapeutic strategies that would be impossible to implement by human therapists. In this sense, the Driver's Simulation Environment for Arm Therapy [24] and Mirror Image Movement Enabler [25] are two robotic devices that have demonstrated that using assistive and resistive forces can promote correct movement patterns while performing bimanual exercises. In addition, robotic devices can be combined with virtual games [26] to promote the motivation and compliance of patients using these devices. However, some disadvantages of robotic devices are their high purchase cost, large size, and complexity, which often limit their use in home therapy. One alternative to this problem is complementing the use of robotic devices in hospitals and clinics with the use of commercially available technology in the home.

In the past few years, there has been an increase in the number of motion tracking technologies developed for video gaming (e.g., Nintendo® Wii™, Microsoft® Kinect™, and PlayStation®

Move). While these systems collect information about the motions made by their users, they also give us the possibility to use augmented feedback (e.g., visual, auditory, haptic) to inform them about their progress and quality of their movements. Moreover, this technology can be used at home and acquired at a low price. Unsurprisingly, the use of this technology has already been incorporated in different rehabilitation studies [27] and has shown promising results for increasing the activity, motivation and functional levels of patients who use them in therapy.

Commercially available tracking technology and augmented feedback can potentially be used to improve the movement patterns of stroke survivors and to reduce their compensatory movements. In a study by Brokaw et al. [28], a Kinect camera and a haptic robotic device tracked the movements of a subject in reaching tasks. Only one healthy subject was tested as a pilot of the system and only unimanual reaching was performed; however, the use of the Kinect camera proved to be an inexpensive and effective alternative to other conventional physical sensors (accelerometers, gyroscopes) since it does not need to be attached to the person, and a single camera can track several joints. Moreover, the use of haptic devices to cue users about their movement could be a substitute of or complement to current larger and more expensive robotic devices. In another study, Alankus et al. [29] used two Wii remotes to measure shoulder abduction/adduction and trunk lateral lean. In this study, they also designed an adaptive video game that used the compensatory motions as a variable in the game. Eleven stroke survivors participated in their experiments, and the games were played in their homes under the investigators' supervision. In their experiments, compensation was reduced, which demonstrates that using commercially available tracking technology is a promising strategy to tackle the problem of compensation in unsupervised therapy.

1.4 Research Questions and Objectives

The main objective of this dissertation was to investigate if augmented feedback (provided by robotic devices and commercially available technology) could be employed to reduce stroke survivors' trunk compensation. To achieve this goal, three different studies (presented in detail in Chapters 2-4) were designed to answer the following research questions:

1. *Does the Distance and Height to Targets Affect the Trunk Movements of Stroke Survivors? (Chapter 2)*

   The first step of this work was to obtain a better understanding of how healthy controls and stroke survivors use their trunk when reaching forward with both hands. Chapter 2 presents the results from this study, in which stroke survivors and healthy controls reached with both hands towards virtual targets placed at different heights. In order to move towards the targets, participants had to move two robotic devices that monitored their hand movements. In addition, a motion tracking camera was employed to measure the level of trunk compensation.

2. *Could Visual and Force Feedback Cues Reduce Stroke Survivors' Trunk Compensation? (Chapter 3)*

   After learning how stroke survivors compensate in a bimanual task, Study 2 proceeded to investigate if augmented feedback (visual or force) could be employed to reduce trunk compensation. This study, presented in Chapter 3, explored how force (provided by two robotic arms) and visual (provided through a computer monitor) feedback could reduce trunk compensation in a cohort of hemiparetic stroke survivors.

3. *Does Adding Game Scores to a Virtual Reaching Task Result in a Larger Reduction of Trunk Compensation when Compared to Biofeedback Alone? (Chapter 4)*

   As video games offer the possibility to employ motivating and engaging environments in which rehabilitation could occur, Study 3 explored (Chapter 4) whether providing participants with in-game rewards (points) in addition to biofeedback (visual+force) could elicit any improved change in their motor behavior when compared to biofeedback alone. For this study, visual and force feedback were combined based on the results from Study 2, in which a large proportion of participants expressed that they wanted to receive both feedback conditions when training to reduce their trunk compensation.

Chapter 2: Trunk Compensation during Bimanual Reaching at Different Heights by Healthy and Hemiparetic Adults[2]

2.1 Introduction

People with hemiparesis tend to compensate for lost function by taking advantage of the redundant degrees of freedom of their bodies. For example, they may use a shoulder hike to compensate for lack of elbow flexion when lifting their arms, or use the unaffected hand to complete tasks that would normally involve the affected side. By using these compensatory movement strategies, individuals manage to maintain the ability to interact with the surrounding environment. However, in general, compensatory movements should be minimized when possible as they can be considered maladaptive [10], [30].

A common compensatory movement when reaching [2] and orienting the hands for grasping [12] is anterior trunk displacement. Although a healthy unimanual forward-reaching movement does involve trunk displacement, the magnitude of displacement is more than 4.5 times greater in stroke survivors [14]. Moreover, hemiparetic stroke survivors tend to use trunk displacement even when the target is well within arm's reach [15]. Evidence suggests that training the arm movements of stroke survivors while limiting the amount of trunk displacement can lead to

[2] A version of Chapter 2 has been published. B.A. Valdés, S.M.N. Glegg, H.F.M. Van der Loos, "Trunk Compensation during Bimanual Reaching at Different Heights by Healthy and Hemiparetic Adults", Journal of Motor Behavior, Published online: December 9th, 2016, www.tandfonline.com/doi/abs/10.1080/00222895.2016.1241748

improvements in arm reaching kinematics, i.e., increased elbow extension and shoulder flexion [3].

In the stroke literature, most of the attention on compensatory movements has been given to the study of unimanual reaching and its connection to trunk compensation [2], [12], [14], [31]. However, older adults tend to use both hands at the same time for most of their daily activities [6]. Furthermore, evidence suggests that practicing bimanual movements leads to the coupling of homologous muscles in both limbs, which promotes the activation of both cerebral hemispheres [7]. Moreover, in healthy individuals, bimanual training can lead to improvements in unimanual performance [9]. Therefore, including therapy exercises that involve bimanual co-ordination is crucial if we want stroke survivors to regain their lost bimanual abilities.

During activities of daily living, people are required to reach in a three-dimensional space, and are not constrained to the transverse plane. However, when trunk compensation has been investigated using unimanual tasks, little attention has been given to the effect of target height on trunk compensation and reaching performance. This study aims to complement the current unimanual and limited bimanual [32] compensatory literature, by analyzing anterior trunk displacement, completion time, symmetry and straightness of the hands' movements during a bimanual reaching task. Targets at different elevations were included to investigate the effects of target height on the reaching performance of both healthy and hemiparetic participants.

2.2 Methods

2.2.1 Participants

Ten hemiparetic stroke survivors (Table 2.1) were recruited through local community centers, private rehabilitation clinics, stroke recovery groups, and the research group's website. The inclusion criteria admitted adults with hemiplegia as a result of a non-traumatic stroke at least six months prior to the study. Participants were also required to have the ability to maintain a sitting position in a chair without arm rests and to move their affected arm from their knee to their chest and back without any assistance from their strong side. Participants were excluded if they had upper-limb surgery in the past 6 months, shoulder subluxation or significant shoulder or trunk pain, uncorrected visual impairments, or any other orthopaedic or neurological conditions that could affect their arm or trunk.

Table 2.1 Demographic and clinical data for stroke participants

	Sex	Age	Height (cm)	DHBS	PS	Lesion Site	Type of Stroke	Time since stroke (months)	FMA	MAS Biceps	MAS Triceps	MAS Wrist Flex.	MAS Wrist Ext.
S-01	M	66	180.0	R	L	R DB of PCA, IC/T	H	34	62	0	0	1	1
S-02	M	56	177.8	R	L	R BG	H	20	25	2	2	2	3
S-03	M	75	177.8	R	R	L P	I	20	60	0	0	0	0
S-04	M	67	167.6	R	L	R CN, PL of R IC, L EC	I	37	39	1	2	2	0
S-05	M	58	177.8	L	L	R F	H	72	46	2	2	2	2
S-06	M	51	170.2	R	R	L CR	I	15	51	1	0	0	1
S-07	M	59	177.8	R	L	R SF	I	12	60	0	0	0	0
S-08	F	75	152.4	R	L	R LN, EC	H	8	66	0	0	0	0
S-09	M	74	185.4	R	R	L MCA	I	24	58	0	0	0	0
S-10	F	73	162.6	R	L	R MCA	I	96	45	1+	1	0	1+
Average		**65.4**	**172.9**					**33.8**					
SD		**8.9**	**9.8**					**28.5**					

BG=Basal Ganglia, CN=Caudate Nucleus, CR= Corona Radiata, DB=Deep Branch, DHBS=Dominant hand before stroke, EC=External Capsule, F= Frontal, FMA=Fugl-Meyer, H=Hemorrhagic, IC=Internal Capsule, I=Ischemic, L=Left, LN= Lentiform Nucleus, MCA= Middle Cerebral Artery, MAS=Modified Ashworth, PS=Paretic side, P=Pontine, PCA= Posterior Cerebral Artery, PL= Posterior Limb, R=Right, SF=Sylvian Fissure, T=Thalamus

The control group included seven females and three males, with a mean age of 65.2 ± 8.68 years, and a mean height of 165.8 ± 9.7 cm. All the participants in this group were right hand dominant. The inclusion criteria were over age 45, with no previous stroke or significant brain injury, and the ability to maintain a sitting position in a standard chair.

All participants provided written informed consent (Appendix A.1). The study was approved by the Clinical Research Ethics Board of the University of British Columbia.

2.2.2 Clinical Assessment

Prior to the reaching protocol, stroke participants were administered the Modified Ashworth Scale (MAS) (Appendix B.1) to measure abnormal muscle tone through resistance to passive movements [33] as a means of describing the sample. This assessment was selected because muscle overactivity can interfere with movement and cause abnormal posturing [34] that may influence participants' performance on the reaching tasks involved in the study. This clinical information about the sample can help readers to determine the generalizability of the findings. Standardized administration methods as described by Bohannon & Smith [33] were used to assess the biceps, triceps and wrist flexors and extensors. The upper extremity subsection of the Fugl-Meyer Assessment (FMA) (Appendix B.2) was also administered as a descriptive measure of performance-based upper extremity impairment severity using standardized procedures described by Sullivan et al. [35]. Greater severity of motor impairment as indicated by lower FMA scores has been correlated with decreased functional ability in daily activities [35]. An occupational therapist with several years of experience in neurorehabilitation performed both clinical assessments. Results are presented in Table 2.1.

2.2.3 Experimental Setup

The experimental system (Figure 2.1) consisted of two haptic robotic devices (Geomagic Phantom Premium 1.5, 3D Systems Geomagic, Rock Hill, SC, USA), a motion tracking camera (Microsoft Kinect v1, Microsoft Corporation, Redmond, WA, USA), and a computer running Windows 7 (Microsoft Corporation, Redmond, WA, USA).

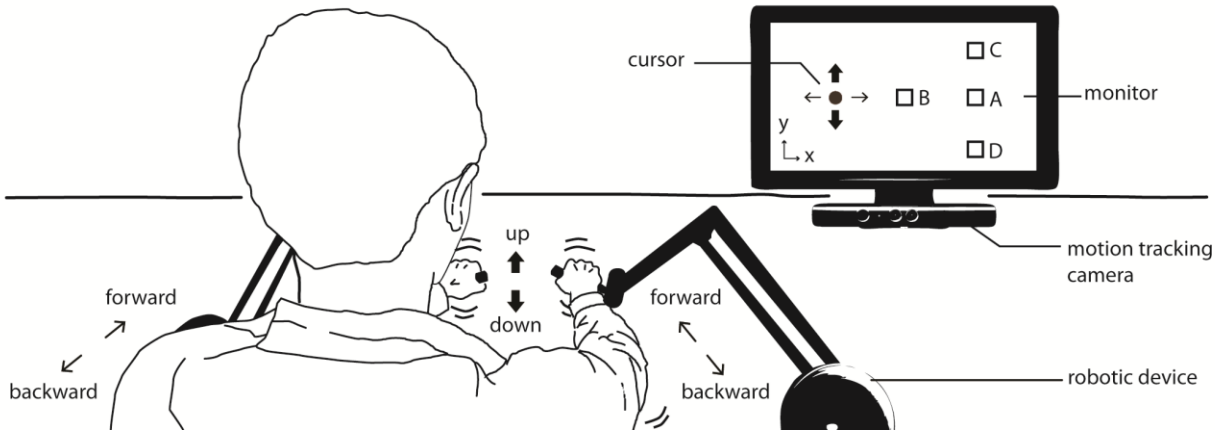


Figure 2.1 Experimental setup

Up/Down and Forward/Backward movements of the hands were mapped to up/down (y-axis) and left/right (x-axis) cursor movements, respectively. Left/Right movements of the hands were not mapped. On each trial, only one target was presented to the participant. Target A = 90% fully extended arm at xiphoid height, Target B = 50% fully extended arm at xiphoid height, Target C = 90% fully extended arm at shoulder height, Target D = 90% fully extended arm at knee height.

For the system, the positive X axis was to the right of the participant, the positive Y axis was pointing up, and the positive Z axis was in the forward direction (towards the camera). The Kinect camera measured trunk anterior displacement in the sagittal plane, which was defined as the displacement of the tracked skeleton's sternal joint in the Z direction. This camera has the potential to be used in at-home rehabilitation programs because of its low cost and commercial

availability. The resolution (X and Y: 3.4mm and Z: 12mm [36]) and displacement accuracy in the depth direction (~25 mm [37], [38]) were deemed sufficient to measure the relative trunk displacement of stroke survivors and healthy participants, based on the magnitude of compensation measured in previous unimanual studies [2], [12], [16].

Participants performed bimanual reaching exercises towards a virtual target by grasping and moving the stylus ends of the two Phantom robots. The devices measured the position of the hands of the participants via the built-in encoders (resolution: 0.03 mm [39]). All motors were turned off, and no forces were produced by the robots.

A monitor was placed in front of the participants to display a targeting game that required them to reach forward to play (Figure 2.2). In addition, the experimenter used another monitor to control the system and display the tracking stability of the Kinect's skeleton and the position of the robots. Only the research team was able to see this monitor during the study. The system was controlled via a custom program built in LabVIEW (National Instruments, Austin, TX, USA), which was able to acquire joint data from the motion tracking camera and the Cartesian position of the robots' end-effectors. The custom program employed libraries from the Kinesthesia and the Phantom Omni Toolkits [40].

Figure 2.2 Side view of reaching movement and setup

2.2.4 Experimental Task

Participants sat in a stationary chair. The backrest was adjusted to keep the trunk of the participant at 90° to the thighs, and to support at least 75% of the thighs in the chair's seat. A custom height-adjustable footrest ensured that all participants had their knees flexed at 90° when seated. The robotic devices were placed on top of a stand on each side of the participant, at a distance that ensured that the workspaces of the robots were large enough to accommodate movements to all targets.

At the beginning of the experiment, the system was calibrated by asking participants to have their trunk against the backrest and to place their hands in front of their xiphoid process, using their thumbs to locate this bony structure. This position would become the starting position for all targets. Users were then asked to fully extend their unaffected arm from the starting position to the following elevations: shoulder height (i.e., arm parallel to the ground), chest height (arm

extended at xiphoid height), and knee height (arm extended downwards without touching their ipsilateral knee).

The calibrated distances were used by the system to place the virtual targets (Figure 2.1) at the following horizontal locations: Target A (90% fully extended arm at xiphoid height), Target B (50% fully extended arm at xiphoid height), Target C (90% fully extended arm at shoulder height), Target D (90% fully extended arm at knee height). The vertical locations of the targets were placed at 90% of each calibrated height. The vertical and horizontal locations were chosen to ensure that participants were able to reach to the targets with their unaffected arm without using any trunk compensation, and to prevent the robotic devices from reaching a singularity. Given that the targets were displayed in a 2D environment, only the Z (forwards/backwards) and Y (up/down) movements of the hands were mapped to the virtual cursor.

After the calibration was completed, our custom bimanual Visual Symmetry (VS) algorithm [41] mapped the movement of the hands to the virtual cursor. This algorithm supported the use of bimanual symmetric movements, in which both hands needed to move the robots' end-effectors at the same time, and in the same direction. In contrast, if only one hand moved or both hands moved in opposite directions there would not be any progression towards the virtual target.

On every iteration of the program (~30Hz), the VS algorithm compared the displacement vectors of both hands to assess which one had the smallest magnitude, and the smallest vector was mapped to the cursor's movement. This approach was used to promote the use of more controlled and symmetrical movements, as large unimanual motions were prevented from

changing the position of the cursor. Figure 2.3 shows the algorithm for mapping the hands' Z movement to the X component of the virtual cursor, where x_c is the X component of the virtual cursor's vector, K_x is the control-display gain for X, z_L is the Z position of the left hand, z_R is the Z position of the right hand, $\boldsymbol{L}$ and $\boldsymbol{R}$ are the left and right hand's displacement vectors, and k is the program iteration number. The control-display gain was defined as the constant multiplier that mapped the movement of the pointing devices to the movement of the virtual cursor. This constant was set based on the subject's arm length and on the screen resolution. Figure 2.3 only shows the mapping for the cursor movement in the X direction; however, this algorithm was also applied to the Y direction using the hands' up/down movement.

$$x_{C,k} = \begin{cases} 0 & if\ k = 0 \\ x_{C,k-1} + K_x(\Delta z_L) & if\ \{[(\Delta z_L > 0) \wedge (\Delta z_R > 0)] \vee [(\Delta z_L < 0) \wedge (\Delta z_R < 0)]\} \wedge \{\|\boldsymbol{L}_k\| < \|\boldsymbol{R}_k\|\}^a \\ x_{C,k-1} + K_x(\Delta z_R) & if\ \{[(\Delta z_L > 0) \wedge (\Delta z_R > 0)] \vee [(\Delta z_L < 0) \wedge (\Delta z_R < 0)]\} \wedge \{\|\boldsymbol{L}_k\| > \|\boldsymbol{R}_k\|\}^b \\ x_{C,k-1} & otherwise \\ & k = 0,1,2,3 \ldots \end{cases}$$

Figure 2.3 Visual symmetry mode algorithm

x_c: X component for virtual cursor vector, K_x: control-display gain for X, z_L: Z position for left hand, z_R :Z position for right hand, L and R are the displacement vectors for the left and right hands, k: iteration number.

[a] If both hands are moving together in the positive or negative direction, and the left hand moved less, then the movement of the left hand is mapped to the virtual cursor.

[b] If both hands are moving together in the positive or negative direction, and the right hand moved less, then the movement of the right hand is mapped to the virtual cursor.

The main objective for the participants was to reach towards a virtual target (one per trial), and to retain the virtual cursor inside the target's bounds for one second. Participants were asked to perform each reach by moving both hands at the same time and in the same direction. In addition, they were asked to move at a comfortable speed, similar to that which they would use during everyday tasks to reach for a physical object. To enable participants to become familiar with the system, they performed five practice trials for each target location, which were presented in a random order, in blocks of four targets. If at any point during the practice run there was a need for system recalibration, the system was reinitialized, and the subject completed 5 trials with the new calibration. After completing each target, participants returned their hands to the initial position before moving on to the next target. To ensure that participants were returning to the correct starting position, verbal and visual guidance to stay within 25 mm of their initial calibrated position was provided. This condition promoted measurement repeatability of upper body movements when reaching to the different targets.

After the practice trials, participants reached towards each target fifteen times, and their trajectories were recorded for data analysis. Targets were presented in a random order in blocks of four, and after completing each target participants were required to return to the initial position. The returning movements towards the initial position were not recorded because during this time participants were free to move without complying with the VS condition.

2.2.5 Data Analysis

Data from the Kinect motion tracking camera and the robots' end effectors were obtained at ~30 Hz. The Kinect joint data, filtered by the Holt Double Exponential Smoothing Method provided by the Microsoft Developer SDK v1.8 [42], reduced jitteriness and stabilized joint positions from the skeletal tracking algorithm.

Anterior trunk displacement provided a measure of trunk compensation employed by participants. This movement was defined as the displacement of the sternal joint of the Kinect skeleton in the Z direction. If at any point during the study the skeleton was observed to inaccurately represent the participant's body (a research assistant monitored the skeleton tracking during all trials), the trial was discarded and repeated at the end of the nominal 15 trials in each block.

To assess the symmetry between the hands, the Root Mean Square (RMS) Error in the Y and Z direction was calculated. The X direction was not calculated, as movements in this direction were not mapped to cursor movement. The error was estimated by taking the difference between the positions of the hands. This calculation was repeated for every data point, and the RMS value for the differences was calculated to obtain the final results.

The index of curvature provided a measure of the straightness of the path of the hands towards the target. This variable was defined as the ratio of the actual 3D hand path to the length of a straight line measured from the starting point to the target. With this measurement, a value of 1 would represent the hands following a perfectly straight path towards the target.

Completion time was measured from the moment the participant was presented with the target until the target was reached and disappeared.

2.2.6 Statistical Analysis

Normality was evaluated using box and normal Quantile-Quantile (Q-Q) plots, as well as the Shapiro-Wilk test. The assumption of equal variances was tested using Levene's Test for Equality of Variance. When the assumption of equal variances was not met, Welch's test was employed instead of the standard t-test. Cohen's *d* was employed as a measure of effect size, with small ($d = 0.2$), medium ($d = 0.5$) and large ($d = 0.8$) effects [43]. Similar to the between-groups comparisons, the effects of the within-groups results were calculated using the standard deviations of each compared group [44].

For repeated measures ANOVA (RMANOVA), the assumption of sphericity was tested using Mauchly's Test. Based on the value of epsilon [45], the Greenhouse-Geisser ($\varepsilon<0.75$) or the Huynh-Feldt ($\varepsilon > 0.75$) corrections were employed.

For pairwise comparisons, when the assumption of normality was met, the paired t-test was employed. In addition to the *p* value, the mean of the differences ($\bar{x}_{diff}$) and its standard error (SE_{diff}) are indicated.

For all post-hoc tests, the *p* values were adjusted using the Bonferroni-Holm correction for multiple comparisons [46].

When the assumption of normality was not met, non-parametric tests were employed for the between- (Mann-Whitney U test) and within- (Friedman and Sign tests) group comparisons. As a result of the non-symmetrical distributions of the differences in the within-group comparison, we were not able to use the Wilcoxon Signed Rank test. Instead, we had to rely on the less powerful Sign test.

Given that the general form of the Mann-Whitney test evaluates stochastic dominance [47], and not location shift, the Probability of Superiority (*PS*) was employed to measure effect size [48]. Since $PS = 0.5$ means equal chance (no effect), as values depart from 0.5, the size of the effect increases. When the Sign test was employed, the Probability of Superiority for dependent groups (PS_{dep}) was used to measure effect size [48]. A PS_{dep} equal to 1 indicates that all values in one level were larger than in the other. In addition to the *p* value of the Sign test, the median (m_{diff}) and the interquartile range (IQR_{diff}) of the differences are indicated in the results.

To measure variability of the data, the coefficient of variation (*CV*) was calculated.

Correlations between the ordinal FMA scores and the ratio variables were analyzed using the Spearman's correlation coefficient (r_s), with very weak (<0.2), weak (0.2 - 0.39), moderate (0.40 - 0.59), strong (0.60 - 0.79), and very strong (0.8 - 1.0) associations [49].

All statistical tests were conducted in SPSS Statistics v22.0 (IBM Corp., Armonk, NY, USA). For calculating the effect size of parametric tests, Dr. Lee A. Becker's [50] effect size calculator was used.

2.3 Results

2.3.1 Between-Groups Comparisons

All participants were able to reach to all targets except for S-10, who only reached Target C nine times instead of the required fifteen, and S-04 who was not able to reach Target C. For both subjects this result was related to their difficulty reaching up against gravity because of low motor function. Results from this section are presented in Table 2.2.

Table 2.2 Control and stroke between-groups comparisons for reaching movements to targets placed at different heights

	Target A		Target B		Target C		Target D	
	Control	**Stroke**	**Control**	**Stroke**	**Control**	**Stroke**	**Control**	**Stroke**
Trunk Displ. (% of target dist.)	11.4 (11.6)	**34.9 (29.3)*** *t(11.76)=2.36 p=0.036 d=1.05*	8.0 (10.1)	31.6 (32.2)	10.7 (10.8)	**28.0 (20.8)*** *t(11.74)=2.24 p=0.046 d=1.04*	17.3 (14.9)	**48.0 (35.3)*** *t(12.11)=2.53 p=0.026 d=1.13*
Trunk Displ. (mm)	29.8 (30.8)	**100.9 (81.3)*** *t(11.53)=2.59 p=0.024 d=1.16*	11.0 (14.4)	**49.6 (49.5)*** *t(10.52)=2.37 p=0.038 d=1.06*	30.0 (30.2)	**92.3 (70.8)*** *t(10.58)=2.45 p=0.033 d=1.14*	32.4 (28.2)	**110.4 (85.2)*** *t(10.95)=2.75 p=0.019 d=1.23*
RMS Error Y (mm)	15.5 [11.4,43.6]	**52.8 (25.6)**** *U=16.0 p=0.009 PS=0.84*	13.5 [12.0,33.5]	**38.3 (17.9)*** *U=18.0 p=0.015 PS=0.82*	19.3 [14.1,33.8]	**49.5 (21.8)*** *U=17.00 p=0.022 PS=0.83*	13.6 [10.7,24.0]	**41.7 (14.9)**** *U=15.0 p=0.007 PS=0.85*
RMS Error Z (mm)	22.0 (7.3)	**35.4 (15.5)*** *t(18.0)=2.47 p=0.024 d=1.11*	19.2 (6.9)	**27.2 (9.3)*** *t(18.0)=2.18 p=0.043 d=0.977*	21.5 (7.4)	**33.6 (12.7)*** *t(17.0)=2.57 p=0.020 d=1.16*	22.4 (9.4)	**38.4 (15.5)*** *t(18.0)=2.78 p=0.012 d=1.25*
Index Curv. Left XYZ	1.3 (0.12)	1.4 [1.2,2.0]	1.6 (0.31)	1.6 [1.5,3.3]	1.5 (0.24)	1.5 [1.3,3.0]	1.5 (0.26)	1.6 [1.4,2.3]
Index Curv. Right XYZ	1.3 (0.10)	1.4 [1.2,2.1]	1.5 (0.33)	1.7 [1.4,3.4]	1.4 (0.23)	1.8 [1.4,3.1]	1.5 (0.24)	1.6 [1.4,2.8]
Time (s)	5.2 (1.3)	5.7 [3.6,9.5]	4.6 (1.4)	4.8 [3.6,11.0]	6.9 (2.2)	6.8 [4.1,16.7]	5.9 (1.1)	5.8 [4.4,11.3]

Mean (SD). Median [1st and 3rd Quartiles]. Significant results are bolded (* $p<0.05$, ** $p<0.01$).
t(degrees of freedom)=t value. p=p value. d=Cohen's d. U=Mann-Whitney U value. PS=Probability of Superiority. RMS=Root Mean Square

2.3.1.1 Trunk Displacement

For all targets, trunk forward displacement values for the hemiparetic group were larger and more variable than for the control group. For the trunk displacement normalized to target distance (Table 2.2), all differences were statistically significant, except for Target B, which was borderline significant ($t(10.75) = 2.20$, $p = .05$). On average, values for Target A (34.9 ± 29.3%) were approximately three times larger for the stroke group, and two times larger for Target C (28.0 ± 20.8%) and Target D (48.0 ± 35.3%). Similar to the trunk displacement results (not normalized), all differences had a large effect.

The stroke group (Table 2.2) exhibited larger values of anterior trunk displacement to all targets. On average, values for Target A (100.9 ± 81.3 mm), C (92.3 ± 70.8 mm) and D (110.4 ± 85.2 mm) were approximately three times larger for the stroke group, and four times larger for Target B (49.6 ± 49.5 mm). All differences had a large effect size.

2.3.1.2 RMS Error

The movements of the hands were more asymmetrical to all targets in the stroke group, with more asymmetry in the direction of gravity. The values for the RMS error in Y and Z, for all targets (Table 2.2), were significantly higher in the stroke group. The median values of the Y errors of the stroke group, for all targets, were close to three times the values in the control group. In addition, the average values for the Z errors of all targets were approximately 1.5 larger in the stroke group. The findings suggest that for all targets, the group's movements tended to be more asymmetrical regardless of the elevation or anterior distance to the targets. In addition, the

values for the superior/inferior direction were larger than those for anterior/posterior, providing evidence of more asymmetrical bimanual movements in the direction of gravity.

2.3.1.3 Index of Curvature

The differences between the indexes of curvature (Table 2.2) for both the left and right hands were found to be statistically non-significant for all targets (all values $p > 0.063$). The index of curvature of the stroke group had large coefficients of variation, which could have played a part in reducing the chances of finding significant differences between groups. In the unimanual reaching literature [2], [14], the index of curvature for stroke survivors tends to be larger than for healthy controls, and results tend to be statistically significant, which provides evidence toward a true difference between groups. Further studies with a larger number of participants could confirm similar results for bimanual reaching.

2.3.1.4 Time

The differences in reaching times between the control and experimental groups (Table 2.2) did not reach statistical significance (Target A, $U = 40.0$, $p = .481$; Target B, $U = 38.0$, $p = .393$; Target C, $U = 42.0$, $p = .842$; Target D, $U = 48.0$, $p = .912$). Similar to the index of curvature, the lack of statistical significance in the differences between groups on the time variable was probably a result of the high variability and small sample size of the stroke group (Target A, $CV = 0.72$; Target B, $CV = 0.58$; Target C, $CV = 0.96$; Target D, $CV = 0.89$). The higher-functioning participants in the stroke group exhibited similar completion times as those in the control group, but for subjects with FMA < 50, in most cases, the mean value and variability of their data tended to be higher than those of the control group.

2.3.2 Within-Groups Comparisons

S-04 was excluded (listwise deletion) from the stroke group calculations only for the within-groups comparisons. This exclusion was made because of the participant's inability to reach the target at shoulder level (Target C) because of limited motor function, which resulted in an incomplete set of data for the omnibus tests (Friedman Test and RMANOVA). All values for the Control group were unchanged (Table 2.2) for the within-group comparisons. The significant results from the pairwise comparisons are presented in Table 2.3.

Table 2.3 Control and stroke within-groups comparisons for reaching movements to targets placed at different heights

	Stroke			Control		
Trunk Displacement (% target distance)	**TD>TA*** $p=0.024$ $m_{diff}=10.53$ $IQR_{diff}=14.39$ $PS_{dep}=1.00$	**TD>TB*** $p=0.020$ $m_{diff}=15.66$ $IQR_{diff}=22.10$ $PS_{dep}=1.00$	**TD>TC*** $p=0.016$ $m_{diff}=7.89$ $IQR_{diff}=23.54$ $PS_{dep}=1.00$	**TD>TB*** $p=0.012$ $m_{diff}=6.62$ $IQR_{diff}=4.29$ $PS_{dep}=1.00$		
Trunk Displacement (mm)	**TA>TB*** $p=0.024$ $\bar{x}_{diff}=44.72$ $SE_{diff}=11.11$ $d=0.789$	**TC>TB*** $p=0.032$ $\bar{x}_{diff}=51.89$ $SE_{diff}=14.66$ $d=0.889$	**TD>TB*** $p=0.020$ $\bar{x}_{diff}=55.70$ $SE_{diff}=13.79$ $d=0.898$	**TA>TB*** $p=0.036$ $\bar{x}_{diff}=18.83$ $SE_{diff}=5.74$ $d=0.782$	**TC>TB*** $p=0.035$ $\bar{x}_{diff}=19.03$ $SE_{diff}=5.47$ $d=0.803$	**TD>TB*** $p=0.018$ $\bar{x}_{diff}=21.44$ $SE_{diff}=5.22$ $d=0.956$
RMS Error Y (mm)	**TA>TB*** $p=0.012$ $\bar{x}_{diff}=11.49$ $SE_{diff}=2.57$ $d=0.613$					
RMS Error Z (mm)						
Index Curvature Left XYZ	**TC>TA*** $p=0.024$ $m_{diff}=0.180$ $IQR_{diff}=0.578$ $PS_{dep}=1.00$					
Index Curvature Right XYZ	**TC>TA*** $p=0.024$ $m_{diff}=0.164$ $IQR_{diff}=0.680$ $PS_{dep}=1.00$					
Time (s)	**TC>TA*** $p=0.023$ $m_{diff}=1.33$ $IQR_{diff}=9.12$ $PS_{dep}=1.00$			**TC>TA*** $p=0.020$ $\bar{x}_{diff}=1.68$ $SE_{diff}=0.436$ $d=0.941$	**TD>TB*** $p=0.012$ $\bar{x}_{diff}=1.29$ $SE_{diff}=0.306$ $d=1.03$	

Significant results are bolded (* $p<0.05$, ** $p<0.01$). *p= p value. m_{diff}=Median of the differences. IQR_{diff}=Interquartile range of the differences. PS_{dep}=Probability of Superiority for dependent groups. $\bar{x}_{diff}$=mean of the differences. SE_{diff}=Standard error of the differences. d=Cohen's d. RMS= Root Mean Square. TA=Target A. TB=Target B. TC=Target C. TD=Target D.*

2.3.2.1 Stroke Group

The target at knee height yielded greater trunk compensation in the stroke group, when compared to targets at other elevations. When trunk displacement was normalized to target distance, the values for Target D were consistently larger than those of A, B and C. Trunk displacement was larger for Targets A, C and D when compared to B.

The RMS error in Y was larger for Target A when compared to Target B. The RMS error in Z did not reach statistical significance in the RMANOVA (p = .053).

The index of curvature for both hands when reaching to Target C was larger than for Target A.

For stroke participants, the time to get to Target C was significantly longer than for Target A.

2.3.2.2 Control Group

After normalizing the trunk displacement with the distance to the target, the values for target D were larger than those for Target B. Trunk displacement for Target B was less than for all the other targets.

The RMS error in Y did not reach statistical significance using the Friedman test (p = .288). A similar result was obtained when using RMANOVA for the error in Z (p = .670).

The index of curvature for the left and right hands did not reach statistical significance when the targets were compared using RMANOVA (Left, p = .097), and the Friedman test (Right, p = .070).

For both groups, the time to get to Target C was significantly longer than for Target A. In addition, for the stroke group, the time to get to target D was longer than for target B.

2.3.3 Correlations with FMA Upper Extremity Motor Scores

Results for this section are presented in Table 2.4**.**

Table 2.4 Correlations with FMA upper extremity motor scores

	Target A	**Target B**	**Target C**	**Target D**
Trunk Displ. (% target dist.)	*r_s=-0.511 p=0.132*	*r_s=-0.474 p=0.166*	*r_s=-0.460 p=0.213*	*r_s=-0.614 p=0.059*
Trunk Displ.	*r_s=-0.584 p=0.077*	*r_s=-0.474 p=0.166*	*r_s=-0.460 p=0.213*	***r_s=-0.644 p=0.044****
RMS Error Y	*r_s=-0.225 p=0.532*	*r_s=-0.091 p=0.802*	*r_s=-0.167 p=0.667*	*r_s=-0.024 p=0.947*
RMS Error Z	*r_s=-0.365 p=0.3*	*r_s=-0.103 p=0.776*	***r_s=-0.828 p=0.006*** **	*r_s=-0.584 p=0.077*
Index Curv. Left XYZ	*r_s=-0.596 p=0.069*	*r_s=-0.389 p=0.266*	*r_s=-0.494 p=0.177*	***r_s=-0.736 p=0.015****
Index Curv. Right XYZ	***r_s=-0.663 p=0.037****	*r_s=-0.322 p=0.364*	*r_s=-0.510 p=0.16*	***r_s=-0.723 p=0.018****
Time[a]	*r_s=-0.374 p=0.287*	*r_s=0.087 p=0.811*	*r_s=-0.311 p=0.416*	*r_s=-0.212 p=0.557*

Significant results are bolded (* p<0.05, **p<0.01).
r_s=Spearman's correlation coefficient. p=p value.
[a]Correlation with the "Coordination and Speed" subscale of FMA.

Trunk displacement normalized to target distance exhibited a non-significant moderate (except for target D, which was strong and close to $p = .05$) correlation to all targets.
Trunk displacement for Target D exhibited a strong statistically significant correlation with the FMA total upper extremity motor score. All the other targets exhibited a non-significant moderate correlation.

The correlations between the RMS errors in Y and the clinical scores were non-significant, weak (Target A) and very weak (Target B, C and D), with all p values above 0.53. For the target at shoulder level, a very strong correlation between the asymmetry of the hands in the anterior/posterior direction and the participants' clinical scores was identified. For the other targets the correlations were non-significant, and very weak (Target B), weak (Target A) and strong (Target D). The correlation between the asymmetry of the hands in the superior/inferior direction toward all different targets was found to be weakly associated with FMA scores. In contrast, the very strong and highly significant correlation between the target at the highest elevation (Target C) and the asymmetry in anterior/posterior could suggest that as the participants move up against gravity, the motions of their hands become more asymmetrical in the transverse plane, and that there may be a direct relationship with decreasing clinical scores. Moreover, two of the participants with lower functional scores (S-04 and S-10) were unable to reach to the highest target the same number of times as the other participants (S-04: 9/15 reaches, S-10: 0/15 reaches), which provides more evidence for this hypothesis. However, the participant with the lowest score (S-02) was able to complete all trials, which calls for a larger sample of participants to be able to generalize these results, and perhaps further exploration of individual

variation and kinematic variables that may help to monitor reaching impairment in the direction of gravity.

The index of curvature of both hands to the target at knee height was strongly correlated with the clinical scores. For all other targets the correlation was non-significant, moderate and weak. For the right hand, the correlations for Targets A and D were strong and significant. For targets B and C the correlations were non-significant, weak, and moderate, respectively.

The reach time was not significantly correlated with either the FMA total upper extremity score or the coordination and speed subscale. The non-significant and weak correlation between the reach time and FMA score could be explained by the lack of a time limit or pressure to hit the target. In the present study, it was more desirable to have participants reach as naturally as possible (at their own pace), in order to allow us to measure trunk compensation values that were closer to those presumably used during everyday reaching tasks.

2.4 Discussion

2.4.1 Trunk Compensation

In stroke survivors, anterior trunk displacement during forward reaching is a common compensatory movement that is typically paired with decreased contribution at the elbow [2],[15]. Muscle synergies are commonly used to account for a reduction in the resulting degrees of freedom of the upper limb during functional reaching tasks [51]. One of the primary goals of post-stroke rehabilitation is to promote the re-learning of pre-injury motor patterns as a means of improving function [1]. A focus on the recovery of healthy-state motor patterns over the use of

compensatory strategies may help to limit loss of range of motion and learned non-use over the long term, as well as to optimize the potential for ongoing improvements into the chronic stage of stroke by means of neuroplasticity [1].

In most previous studies, participants have only been asked to perform reaching movements unimanually and to a single height [14], [16], [31]. In this study, we investigated if participants would exhibit similar levels of trunk compensation when asked to reach bimanually at different heights and distances. This information is important because many functional tasks involve bimanual reaching at a range of heights, and a more thorough understanding of the degree to which the addition of the less affected arm to the reaching task may affect trunk displacement has implications for the way therapy is structured.

Values for trunk displacement during reaching to targets at shoulder, knee and chest height were larger in the stroke group, when compared to the control group. These results are consistent with what has been documented previously for targets at chest height for bimanual [32] and unimanual reaching [2]. Trunk compensation as a percentage of the target distance for Target B (target at 50% of arm reach) was found to be borderline significant ($p = .05$) when comparing the stroke and control samples. In previous unimanual studies [14], [31], the trunk compensation of stroke survivors when reaching to near targets tended to be higher when compared to the results of the control group. Consequently, we attribute this borderline result to the low number of subjects and their high variances. In addition, the within-group significant results for both the stroke and control groups support the idea that the trunk displacement required to reach Target B was less than for all the other targets.

When comparing the trunk compensation normalized to target distance, the stroke group (within-group comparisons) exhibited consistently larger values when reaching to the target below the chest (Target D) than for all the other distances and elevations, which supports the idea of a relationship between moving in the direction of gravity and the amount of trunk compensation used by stroke survivors. We hypothesize that the reason for larger trunk flexion for targets below the xiphoid process height is that for stroke participants to reach down to a target, they can successfully complete the movement by employing only trunk flexion, with minimal shoulder and elbow movement. On the other hand, if the target is placed above sternal height, utilizing only trunk flexion will move the participant's hand downwards, requiring greater abduction at the shoulder to move the hand upwards, which is a movement that may be more challenging for hemiparetic participants in the presence of flexor synergies [52]. As a result, it would appear that stroke survivors select the movement that requires the least shoulder abduction to reach targets in front of them. Trunk flexion for unimanual reaching towards targets below chest height appears to show a similar trend for healthy older and young adults reaching to physical targets placed in front of them [53]. During data analysis, before we applied the multiple comparisons corrections to the *p* values of the control group, the results for Target D were observed to be the same as those of the stroke group ($p = .021$), which is consistent with the aforementioned study.

Trunk displacement to Target D exhibited a strong correlation with the FMA upper extremity motor scores. This result suggests that stroke survivors with lower FMA scores tend to exhibit more compensatory anterior trunk displacement, especially when they reach towards targets below chest height. The non-significant correlations between the clinical scores and the trunk displacements to the targets at chest level (Targets A and B) differ from previous findings for

unimanual reaching [2], [12], [14], [31]. This difference could be the result of the low power of the study afforded by the small sample size. However, the strength of the associations was moderate, and the fact that results for Target D were significant even with the small sample suggests that a clear correlation exists between the clinical scores and the trunk compensation used for targets that require the participants to move in the direction of gravity, a reaching height which has not been thoroughly studied in the stroke literature.

For both the left and right hand, the correlation between the index of curvature of Target D and the FMA scores was strong and significant. This finding provides evidence to support the idea that for targets below xiphoid process height, participants tend to move both hands in a less straight trajectory when their motor function is more impaired. Because the main driver for their progression towards the target was trunk flexion, small movements about the hip joint could have resulted in larger displacements of the hands as compared to reaching with a static trunk, resulting in more uncontrolled movements.

2.4.2 Bimanual Performance

Chronic stroke survivors tend to use their unaffected side 3-6 times more than their affected side for daily activities, and when they do perform bimanual activities, their affected limb is used with less intensity than the unaffected limb [54], [55]. In contrast, healthy individuals perform bimanual tasks with greater frequency than unimanual tasks during daily activities [6]. Post-stroke, increased bilateral upper limb use is also associated with improved task performance in instrumental activities of daily living [56]. Consequently, rehabilitation approaches that promote the use of the affected limb in both unimanual and bimanual exercises may be particularly

effective at increasing the overall use of the affected arm, while enabling stroke survivors to practice movements that are closer to those typically employed in everyday tasks. Moreover, in their review of the literature on bimanual movements, Cauraugh and Summers [8] suggest that bimanual training after a stroke could facilitate neural plasticity as a result of the recruitment of ipsilateral pathways, motor cortex disinhibition, and increased use of corticopropriospinal pathways. As such, clinicians can exploit the neural benefits of practicing bimanual movements through the design of such rehabilitation interventions for stroke survivors. Indeed, bilateral training has been found to be as efficacious as unimanual approaches at improving function of the paretic arm [55].

In this study, we employed a bimanual system to investigate the trunk compensation of stroke survivors and healthy controls. As a measure of bimanual performance, we employed the RMS error between the hands' movements. Based on the results for the hands' asymmetry, we hypothesize that the reduction in the active upper limb range of motion (ROM) at higher reaching elevations is a result of the difficulty to lift the paretic arm using shoulder abduction and flexion, while accompanied by elbow extension. This reduction in the ROM during movements that require larger shoulder abduction torques appears to be connected to upper limb flexor synergy [57]. In addition, in the within-group comparisons, the stroke group took more time to reach to the target at the highest elevation (Target C) than to the target at chest level (Target A), which again provides support to the idea that the higher the stroke participants tried to reach, the more difficult the task became. For the control group a similar result was observed when comparing those targets, which suggests that for both populations, the larger torques required to sustain the arm at higher elevations directly impact the difficulty of the task.

Furthermore, the index of curvature of the stroke group was larger for Target C than for Target A, which again supports the idea that stroke survivors may experience increasing difficulty during reaching tasks at higher elevations. Conversely, the control group did not exhibit any effect of gravity on the index of curvature to the different targets.

This information confirms clinical observations that inform the grading of the degree of reaching task challenge based on target height. More importantly, however, is the implication that kinematic information about the symmetry of the hands' movements could provide clinicians with an objective measurement of bimanual performance over the course of rehabilitation for hemiparesis, with lower means and variability implying more symmetrical bimanual movements. This analysis could provide a means of monitoring upper limb improvement over time [58]. However, further longitudinal research over the course of the rehabilitation process would be warranted to confirm this method.

2.4.3 Clinical Implications

The results from this study provide supporting evidence for the hypothesis that hemiparetic stroke survivors employ different magnitudes of trunk compensation when asked to reach to different heights. This information is relevant for clinicians promoting premorbid movement patterns during the rehabilitation of the upper extremities post-stroke. One of the main goals of physical rehabilitation programs is to maximize functional independence through retraining of daily skills [59]; this study supports the concept of performing movements in all directions as being an important consideration in optimizing the patient's recovery, as stroke survivors employ different motions strategies to reach at different elevations. As newer technologies for

rehabilitation become available e.g., robotic, virtual, and gaming rehabilitation [27], [60], the approach of performing movements in 3D space should be paramount in the design of these applications.

Previous studies [13], [16] have provided promising results about how limiting trunk motion can lead to improvements in arm movement quality. These studies have employed physical trunk restraints to limit the trunk movement of stroke survivors [3]. An alternate approach could be to employ augmented feedback to provide information to hemiparetic patients about their trunk compensation in real-time [17], [29]. Consequently, the results from this study could provide guidance on the different levels of compensation that participants may exhibit when asked to reach at different distances and heights.

The novel integrated system that was presented in this work has the capability of measuring different kinematic aspects of the movements of the hands, arms and trunk. The analysis of these types of kinematic data has the potential to generate indicators of improvement during rehabilitation, which could complement the information obtained by current clinical scales of impairment and function, to further customize and evaluate the outcomes of therapist-prescribed treatment programs.

2.4.4 Study Limitations

A limitation of this study was the Kinect's accuracy and resolution (Experimental Setup section), which does not allow for the sub-millimeter accuracy of other more expensive and complex systems (e.g., Vicon). However, in this study, the Kinect was able to capture the relative

displacements of the trunk for both healthy and stroke survivors, and showed clear differences between populations and targets. The release of Kinect v2, which has a higher resolution and improved skeletal tracking, has the potential to offer an enhanced tracking option for future rehabilitation/motion capture projects.

A second limitation was the mapping of the hand's movements from a forward/backward end effector motion, to a left/right cursor movement on the screen. To mitigate the effects of this mapping on the participants' "normal" motion strategies, we provided them with a set of 20 reaches as part of the familiarization stage. During the practice trials participants could spend as much time as needed to complete the target reaches, giving them enough opportunity to explore how their hand movements mapped to the virtual cursor.

Finally, a larger sample size should be employed in future studies to further examine the ideas presented in this work.

2.5 Study 1 Conclusions

Activities of daily living require stroke survivors to reach in a three-dimensional space with variable joint positions/orientations. As a result, employing virtual/robotic rehabilitation systems that promote the use of movements that would be required for users to interact with the real world is crucial. Robotic/virtual systems should not focus on training users in one plane of motion, but instead should promote the use of reaching motions within the entire arm's workspace. In the stroke reaching literature, trunk displacement is identified as a major component of the reaching movements of stroke survivors; however, how this movement is

affected by different height requirements had not been yet thoroughly examined, especially for bimanual interventions.

The results obtained in this work provide evidence that stroke survivors exhibit different degrees of trunk compensation and hand asymmetry during reaching to different elevations. We believe that this information is particularly important for virtual/robotic rehabilitation programs that aim to reduce trunk compensation and to promote premorbid movement patterns.

Chapter 3: Reducing Trunk Compensation in Stroke Survivors: A Randomized Crossover Trial Comparing Visual vs. Force Feedback Modalities[3]

3.1 Introduction

Stroke survivors with limited upper extremity (UE) motor function due to hemiparesis use their trunk to compensate when reaching forward [12], [15], [61]. Relying on these compensatory movements to reach can be detrimental to UE recovery [1]. Moreover, reducing the magnitude of trunk compensation by restraining the trunk can lead to improvements in UE movement quality [10], [13], [62].

One method used to reduce trunk compensation is trunk restraint [63], which physically restrains the person to a chair using straps or a custom harness. An alternative is employing technology to provide augmented feedback ("information about an action provided by a source external to the performer" [64]) to individuals about the magnitude of their compensatory movements [17],[29]. This augmented feedback strategy offers advantages when compared with trunk restraint: the person makes a conscious choice not to compensate, rather than relying on physical restraints that continuously limit body movement; it is less intrusive as there is no need to restrain the person to a chair; it can be employed at home without direct supervision; the feedback intensity

[3] A version of Chapter 3 has been published. B.A. Valdés, A.N. Schneider, H.F.M. Van der Loos, "Reducing Trunk Compensation in Stroke Survivors: A Randomized Crossover Trial Comparing Visual vs. Force Feedback Modalities", Archives of Physical Medicine and Rehabilitation, Published online: May 17th, 2017, https://doi.org/10.1016/j.apmr.2017.03.034

can be modified in real time from a remote location; and the active error thresholds and challenge of the task can be automatically adapted as the individual improves. To adopt augmented feedback in common rehabilitation practice, there must be sufficient evidence supporting the efficacy of these alternate feedback methods. In this study, we employed two augmented feedback modalities (visual and force) to provide information to participants about their trunk compensation. The objectives of this study were to investigate: (1) Whether the compensatory trunk movement of stroke survivors can be decreased by force and visual feedback during reaching tasks; and (2) Whether one of these feedback modalities is more effective in reducing compensatory trunk movement.

3.2 Methods

3.2.1 Participants

Fifteen participants were recruited (Table 3.1) from stroke recovery groups, the research group's website, and the community. The enrollment, allocation, and assignment of participants were conducted by the author (Figure 3.1). The allocation sequence was stored on a digital file, and the participants were not aware of their allocation until after the familiarization with the system was completed and the baseline measurements were taken. A previous controlled trial [16] that investigated the reduction of stroke survivors' trunk compensation using trunk restraint provided the rationale for the chosen sample size. Participants provided written informed consent (Appendix A.2), and the study was approved by the Clinical Research Ethics Board of the University of British Columbia.

Table 3.1 Demographic and clinical data for stroke participants

	Sex	Age (years)	Height (cm)	DHBS	PS	Type of Stroke	Time since stroke (months)	FMA (max. 66)	RPS (max. 36)
S-01	M	58	178	R	L	H	38	28	5
S-02	F	80	156	R	L	H	47	45	23
S-03	M	58	178	L	R	H	24	38	13
S-04	M	65	170	R	R	I	48	46	26
S-05	F	45	172	R	L	I	26	55	31
S-06	F	58	157	R	R	I	180	32	14
S-07	F	71	152	R	L	H	13	43	28
S-08	M	48	170	L	L	I	31	29	5
S-09	M	83	170	R	L	I	11	19	9
S-10	M	69	175	R	R	I	114	34	NA
S-11	F	55	163	R	L	I	79	47	33
S-12	M	69	168	R	L	I	69	46	29
S-13	M	62	178	R	R	I	22	58	34
S-14	M	77	178	R	R	I	31	59	29
S-15	M	66	178	R	R	I	132	15	7
Average		**64.27**	**169.53**				**57.67**	**39.60**	**20.42**
SD		**11.02**	**8.66**				**49.17**	**13.36**	**11.02**

DHBS=Dominant hand before stroke, FMA =Fugl-Meyer Assessment, H=Hemorrhagic, I=Ischemic, L=Left, NA= Not Available, PS=Paretic side, R=Right, RPS=Reaching Performance Scale

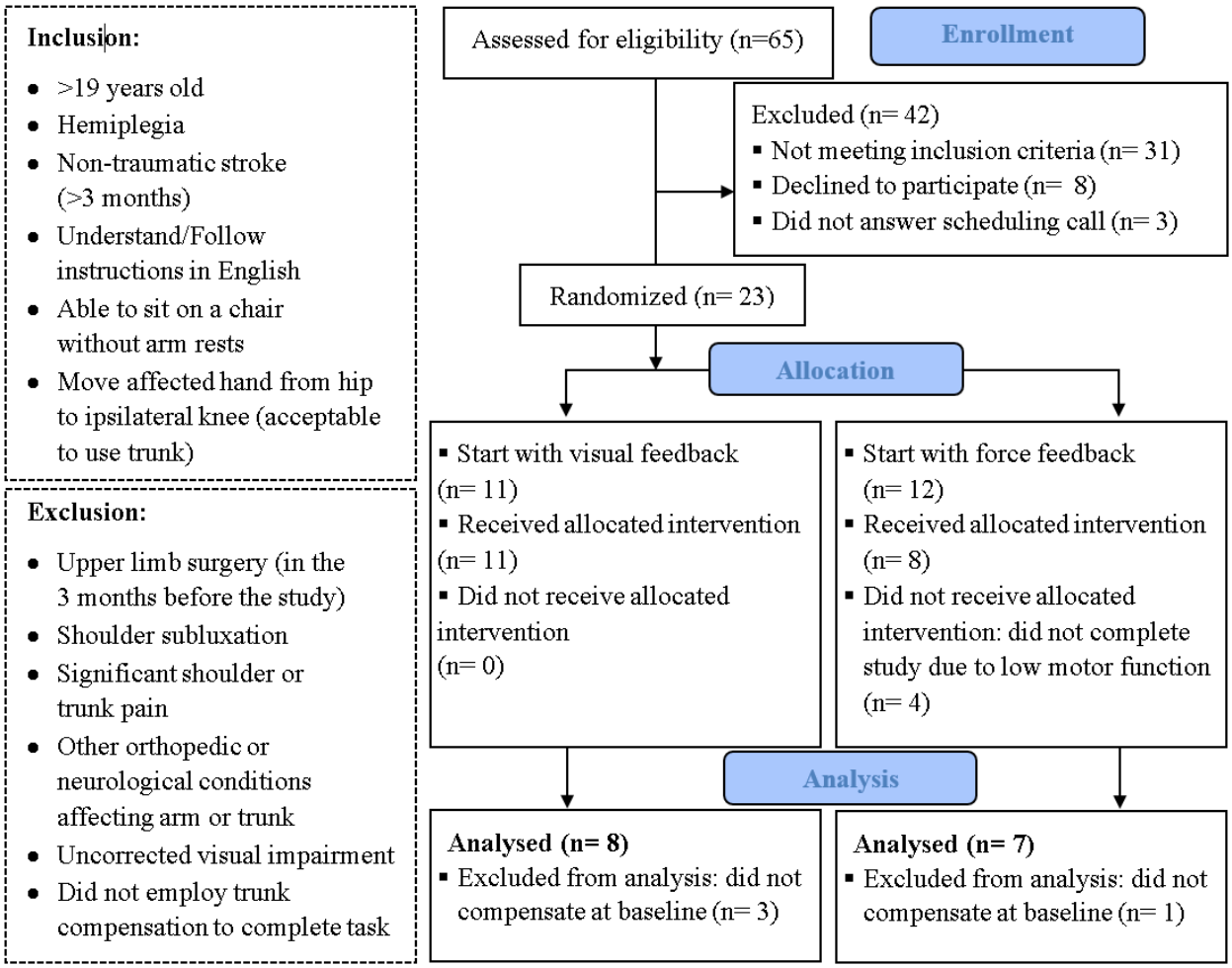


Figure 3.1 Recruitment and allocation

3.2.2 Clinical Assessment

Baseline impairment and compensation assessments were administered by occupational therapists (Table 3.1), which were blinded to the allocation of participants. The UE subsection of the Fugl-Meyer Assessment (FMA) (Appendix B.2) [35] was utilized to measure UE motor impairment. The Reaching Performance Scale (RPS) (Appendix B.3) [65] was used to assess level of participant compensation when reaching forward.

3.2.3 Experimental Design and Randomization

The trial used a crossover design; all participants experienced both treatments, and the order of the treatments was randomized. To reduce order effects, participants were randomly allocated (computerized pseudo-random number generator [66]) to start with visual or force feedback (Figure 3.1). Participants were first stratified according to FMA impairment scores (moderate to severe <50, and mild >= 50 [10], [67]) to ensure group balance, and then randomly allocated to the two treatment groups in blocks of two. Included in the final analysis were eight participants allocated to start with visual feedback, and seven with force feedback. Figure 3.2 details the experimental procedure.

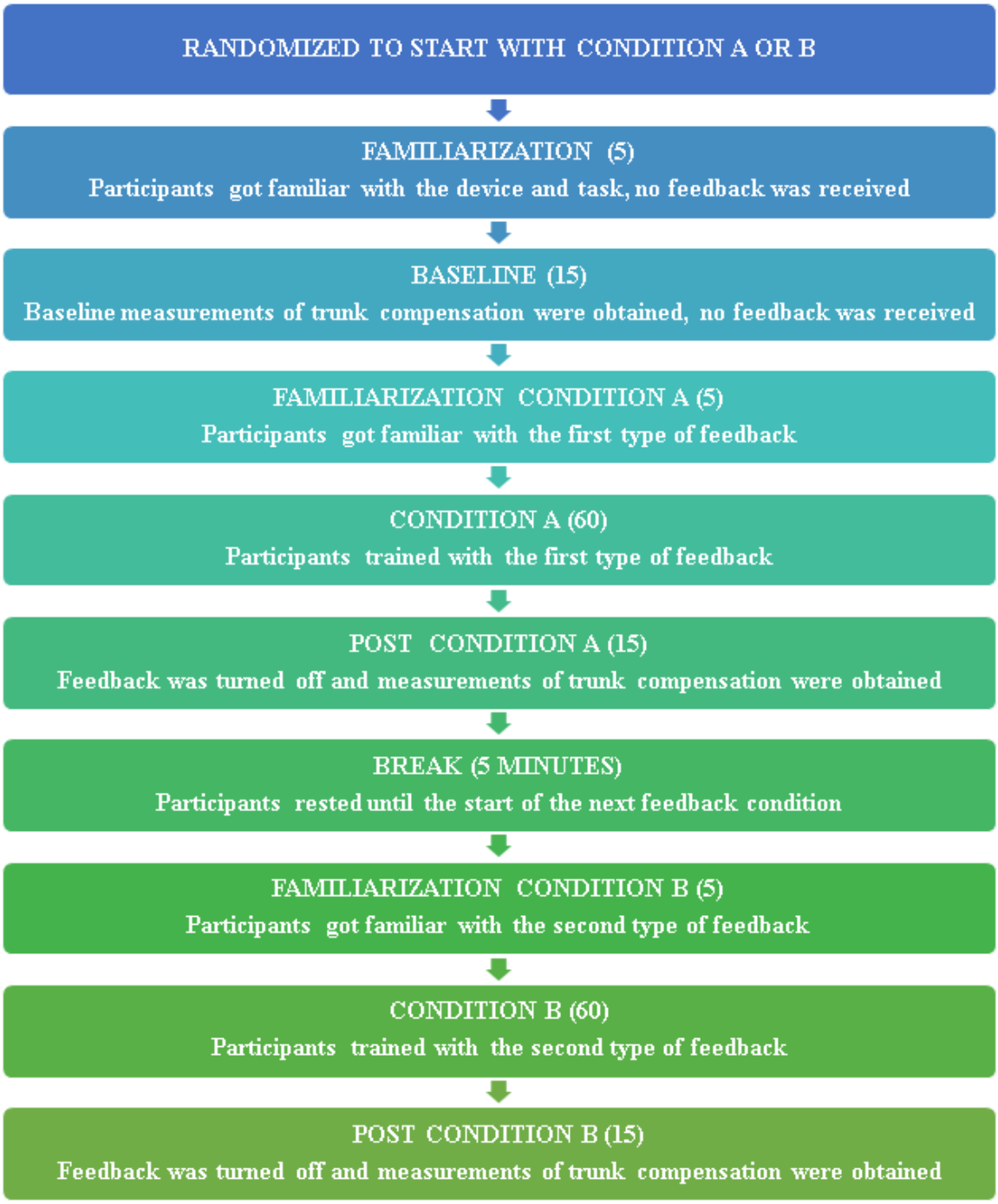


Figure 3.2 Experimental design

Number of trials in parenthesis. Condition A: Visual Feedback, Condition B: Force Feedback. Participants did not receive feedback in any of the post trials. This was a low-risk study, with fatigue being the only possible harm. To reduce fatigue, participants received 1 minute rests after every 15 trials, and were able to rest between targets if requested.

3.2.4 Experimental Setup

The integrated system (Figure 3.3) consisted of two 6DOF JACO v2 (Kinova Robotics, Boisbriand, QC, Canada) robotic arms, a Kinect v2 (Microsoft Corporation, Redmond, WA, USA) motion tracking camera, and a personal computer. The system was controlled through a custom LabVIEW (National Instruments, Austin, TX, USA) program that displayed the reaching task on a monitor. The program employed libraries from the Haro3D Toolkit [68]. Participants sat on a chair with at least 75% of their thighs resting on the seat, and a backrest and footrest adjusted to keep their hips and knees flexed at 90°.

Figure 3.3 Experimental setup

Participants moved the robotic devices while completing the reaching task (displayed in the computer monitor). In addition, a motion tracking camera was placed in front of the participant to monitor trunk compensation.

3.2.5 Experimental Task

Participants were instructed to move two virtual cursors (Figure 3.4) representing each of their hands towards a target, and stay inside target bounds for 1 second. To move the cursors, participants performed symmetrical bimanual reaching movements from their hips to their knees (without touching their thighs), while holding two robotic device handles (Figure 3.3). Moving the robots required minimal resistance, as both robot arms were under admittance control [69] (robot sensed applied force and moved in the same direction). After every trial, participants returned to their initial calibrated position. If participants were unable to hold the robots' handles, they were provided with a wrist splint and a strap.

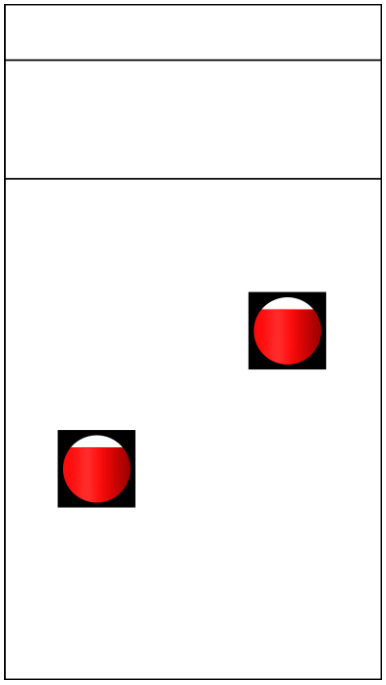


Figure 3.4 Virtual reaching task with visual feedback active

Participants needed to move both cursors inside the target (two horizontal lines near the top of the figure) to complete one trial. When not receiving visual feedback, the cursors would be empty (white) even when participants were exhibiting trunk compensation.

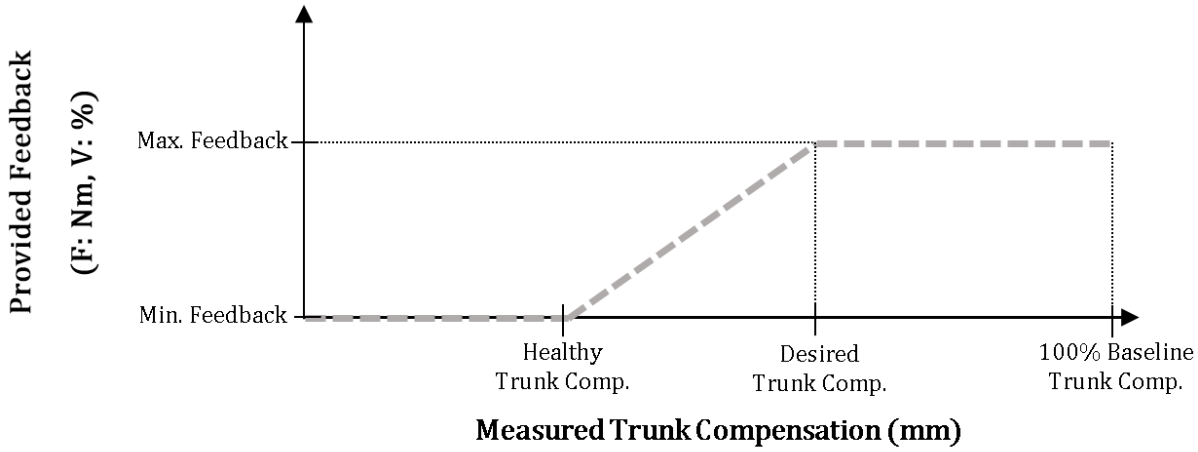
The movement of the cursors was only mapped to the anterior/posterior movement of participants' hands, and the robotic devices were restricted to move in only two directions (up/down and forwards/backwards)[4]. Participants were told that moving up/down would not affect the task, and that they should aim to move both hands at the same time and at a constant height above, and close to, their thighs.

Before the session started, the distance to the virtual target (90% of hip-knee distance) was calibrated by asking participants to move their unaffected hand from their hips to their ipsilateral knee, while keeping their back against the chair. Also, participants were asked to push as hard as possible, with the robotic arms stationary, to ensure that the maximum torque that they could exert was above the maximum force feedback that they would receive (9.5 Nm based on robots' torque limits). This torque was equivalent to the force required to hold a 1.23 kg object. Pilot studies had shown that this force is easily perceived by healthy participants. To ensure that stroke participants could sense the force, all participants confirmed during familiarization trials that they could feel how the force changed as they compensated with their trunk.

The robotic arms provided force feedback when the Kinect motion tracking camera detected that the participant showed anterior trunk displacement during a reaching movement. The feedback adjusted the minimum torque required to move the robotic arms. This type of feedback was chosen because it provided a safety advantage; the robots would not move unless the participants actively moved them, whereas a purely resistive force acting in the opposite direction of motion

[4] Video included in dissertation's online supplementary material.

could harm the participant if they released the robots' handles. Up to the first 30 mm of compensation, participants did not receive feedback, as this was considered to be within the "normal" threshold of healthy compensation [61]. After this threshold, the force feedback was proportional to the amount of trunk compensation (Figure 3.5), and saturated at 50% of the average compensation each participant exhibited at baseline, minus the healthy compensation. The *desired* compensation was then set to 50% to promote achievable improvement in a short-term intervention. Our study involved only one training session; as a result, the desired compensation value was set to a static value. However, for interventions with multiple sessions, this value could be adjusted by therapists/researchers after every session to adapt to the evolving progress of their clients/participants.



$$Provided\ Feedback = m(Measured\ Trunk\ Comp.) + b$$

$$m = \frac{(Max.\ Feedback - Min.\ Feedback)}{(Desired\ Trunk\ Comp. - Healthy\ Trunk\ Comp.)}$$

$$b = Min.\ Feedback - m\ (Healthy\ Trunk\ Comp.)$$

$$Healthy\ Trunk\ Comp. = 30mm$$

$$Desired\ Trunk\ Comp. = 0.5 * (Baseline\ Trunk\ Comp. - Healthy\ Trunk\ Comp.)$$

Figure 3.5 Provided feedback calculation that related trunk compensation to visual and force feedback levels

The dashed lines indicate the level of feedback provided during a reaching movement. Below the healthy trunk compensation value, participants did not receive feedback. Above this value, the feedback was proportional to the measured trunk compensation. For values above the desired trunk compensation, the feedback saturated to its maximum level. Both visual and force feedback levels were updated at the refresh rate of the computer program (~30Hz).
F: Force Feedback. F Max. Feedback: 9.5 Nm. F Min. Feedback: 1Nm.
V: Visual Feedback. V Max. Feedback: 100%. V Min. Feedback: 0%.

The visual feedback operated using the same algorithm as the force feedback (Figure 3.5), and was represented as red ink filling up the virtual cursors, similar to a thermometer filling up, and proportional to the amount of trunk compensation (Figure 3.4). In this condition, the force

feedback was turned off. This visual display was chosen because: it did not add a new element to the screen (avoiding adding to the users' cognitive load); participants would already be familiar with this type of symbol; and it did not require detection of color change, which would be an issue for color-blind people.

3.2.6 Data Analysis

All kinematic variables analyzed were measured during the Baseline, Post Visual and Post Force trials (during these, participants were not receiving feedback). The motion data were obtained from the Kinect and JACO arms at ~30 Hz. The data were then resampled at a constant rate (25 Hz), and low-pass filtered (6 Hz [70]). If any of the Kinect's data points were inferred or not tracked, they were removed from the motion log. The Kinect's v2 spine-shoulder and shoulder joints have been reported to have an average accuracy of ~10 (SD:10) mm with high correlation (0.99), when compared to a gold standard motion capture system [71]. The capabilities of the camera where deemed sufficient to capture trunk compensation from stroke survivors, as their displacements tend to be 30 mm or more [61].

The primary outcome was trunk displacement (anterior displacement of the Kinect's spine-shoulder joint). Secondary outcomes included: Trunk Rotation: angle between the vector created from the left to the right shoulder joints, and the frontal plane (positive angles indicate counterclockwise rotations); Index of curvature: measure of the straightness of the hands' path towards the target in the *Y* and *Z* (superior/inferior and anterior/posterior) directions. The index was defined as the ratio of the hands' path and a straight line. A value of 1 would represent a perfectly straight path; Root Mean Square (RMS) Error in *Y* and *Z*: measure of bimanual

symmetry between the hands' movement. This error was computed as the difference between the hands' position at every iteration of the program, and the RMS error of these values was calculated to obtain the final result. Smaller errors indicated more symmetrical movements; Time: measured from the moment participants were presented with the reaching task to the end of the trial; Post-Test Questionnaire (Likert items and open-ended questions, Appendix C.1): administered at the end of the study to investigate the experience of the participants and the usability of the system using the System Usability Scale (SUS) [72].

3.2.7 Statistical Analysis

To investigate whether there were any differences between visual and force feedback to reduce compensation, an Analysis of Covariance (ANCOVA) was employed with a within-subject factor of treatment (Visual or Force), a between-subjects factor of group (start with Visual or Force), and the baseline measurements used as a covariate. To elucidate whether force and/or visual feedback reduced trunk compensation, the percentage gains (percent change from baseline to post measurements) were compared against a mean value of 0 using a one-sample t-test. When data violated parametric assumptions, the non-parametric Sign-Test was employed. A 95% Confidence Interval (CI) was calculated for significant results. For post-hoc tests, the p values were adjusted using the Bonferroni-Holm correction [46]. Cohen's d was employed as a measure of effect size, with small (d=0.2), medium (d=0.5) and large (d=0.8) effects [43]. Significance level was set at $p < 0.05$.

3.3 Results

When comparing visual against force feedback (Table 3.2, left) for all outcome measures, all of the main effects and interactions of the ANCOVA were not statistically significant ($p > 0.05$). The only exception was the Left Index of Curvature, for which the interaction between treatment and baseline was significant ($p = .001$), which would invalidate the results from the ANCOVA's significant treatment effect ($p = .002$) for this measure. Thus, for the outcome measures employed in this study, there was no evidence that one feedback method was more effective.

Table 3.2 Comparison between post force and post visual variables (left), percentage change from baseline to post measurements (right)

	Post Visual vs. Post Force		
	Baseline	**Post Visual**	**Post Force**
Trunk Displacement (mm)	119.2 (71.7)	69.8 (73.1)	68.7 (64.6)
Trunk Rotation (°)	-1.2 (6.0)	-2.2 (7.2)	-1.5 (6.5)
Time (s)	7.4 (4.2)	5.5 (1.5)	5.7 (2.1)
Index Curv. Left YZ	1.3 (0.67)	1.1 (0.24)	1.1 (0.15)
Index Curv. Right YZ	1.5 (1.4)	1.1 (0.13)	1.2 (0.23)
RMS Z (mm)	22.4 (11.4)	31.1 (29.0)	29.7 (23.9)
RMS Y (mm)	31.6 (25.2)	40.6 (25.4)	35.9 (20.3)

	Percentage change from Baseline to Post measurements	
	Post Visual	**Post Force**
Trunk Displacement (%)	**-45.6 (45.8)**** ***t(14)=-3.86*** ***p=.004*** ***d=0.99*** ***CI: -70.9,-20.2***	**-41.1 (46.1)**** ***t(14)=-3.46*** ***p=.004*** ***d=0.89*** ***CI:: -66.7,-15.6***
Trunk Rotation (%)	17.5 [-19.5, 170.2]	-0.45 [-21.8, 76.2]
Time (%)	-10.4 [-36.9, -2.3]	-14.1 [-28.0, -4.3]
Index Curv. Left YZ (%)	-0.14 [-5.9,6.5]	1.5 [-4.7,4.0]
Index Curv. Right YZ (%)	-3.2 [-6.2, 3.1]	0.16 [-5.4, 5.1]
RMS Z (%)	13.4 [-4.9, 36.3]	9.4 [-12.0, 58.5]
RMS Y (%)	27.0 [-9.3, 121.2]	19.2 [-8.8, 80.1]

Mean (SD). Median [1st and 3rd Quartiles]. Significant results are bolded (* $p<0.05$, ** $p<0.01$). Analysis of Covariance employed to compare Post Visual vs. Post Force (left), T-Test and Sign-Test (values reporting median and quartiles) for percentage change comparisons (right).
CI: 95% confidence interval. d=Cohen's d. p=p value. RMS=Root Mean Square. t(degrees of freedom)=t value.

When investigating if visual and force feedback reduced trunk compensation from baseline (Table 3.2, right, and Figure 3.6), a significant (p = 0.004) large effect (0.99 and 0.89, respectively) was observed for both methods. Individual results are presented in Table 3.3, Figure 3.7, and Figure 3.8. Participants' trunk displacement data during the training trials are presented in Appendix D. For visual feedback: 8/15 participants reduced their compensation by more than 50%, 10/15 by more than 30%, and 2/15 increased their compensation by less than 33%. For force feedback: 8/15 participants reduced their compensation by more than 50%, 8/15 more than 30%, 3/15 increased their compensation by less than 30%. This evidence suggests that augmented visual and force feedback can reduce trunk compensation in hemiparetic stroke survivors. For all other measures, the differences were not statistically significant. Post-Test questionnaire results are presented in Appendix C.2.

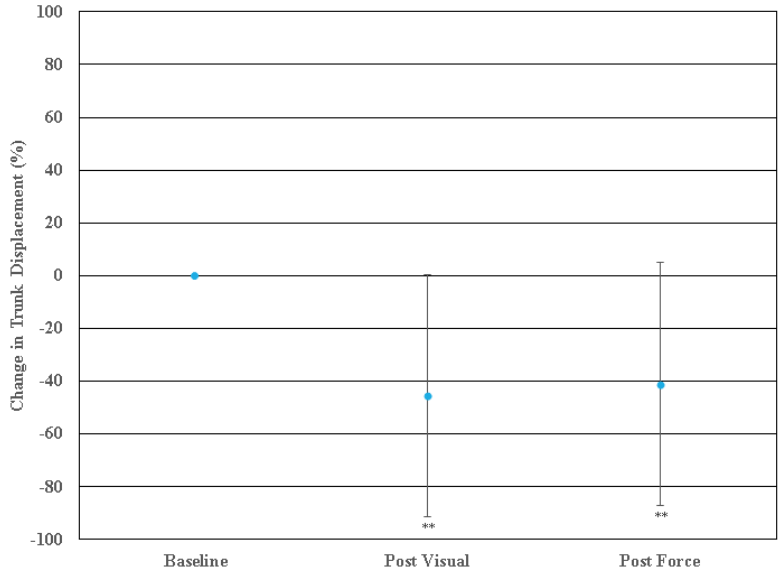


Figure 3.6 Trunk displacement percentage change from baseline to post measurements
Average values are presented with standard deviations indicated by error bars.

Table 3.3 Individual results for trunk compensation

	Baseline (mm)	Post Visual (mm)	Post Force (mm)
S-01[a]	251.6	238.8	1.8
S-02	37.5	-11.5	-11.2
S-03	139.7	184.6	181.3
S-04[a]	74.4	72.4	71.2
S-05	91.3	18.6	44.6
S-06[a]	119.8	8.0	23.0
S-07[a]	154.8	16.7	121.4
S-08	184.4	45.8	83.7
S-09	114.3	103.7	90.7
S-10	189.9	72.4	66.3
S-11[a]	50.3	25.2	19.0
S-12[a]	65.7	76.7	73.4
S-13[a]	45.5	14.1	10.3
S-14[a]	33.5	21.8	38.8
S-15	235.6	159.8	217.1
Average	**119.2**	**69.8**	**68.7**
SD	**71.7**	**73.1**	**64.6**

[a] Participants who started with Visual Feedback

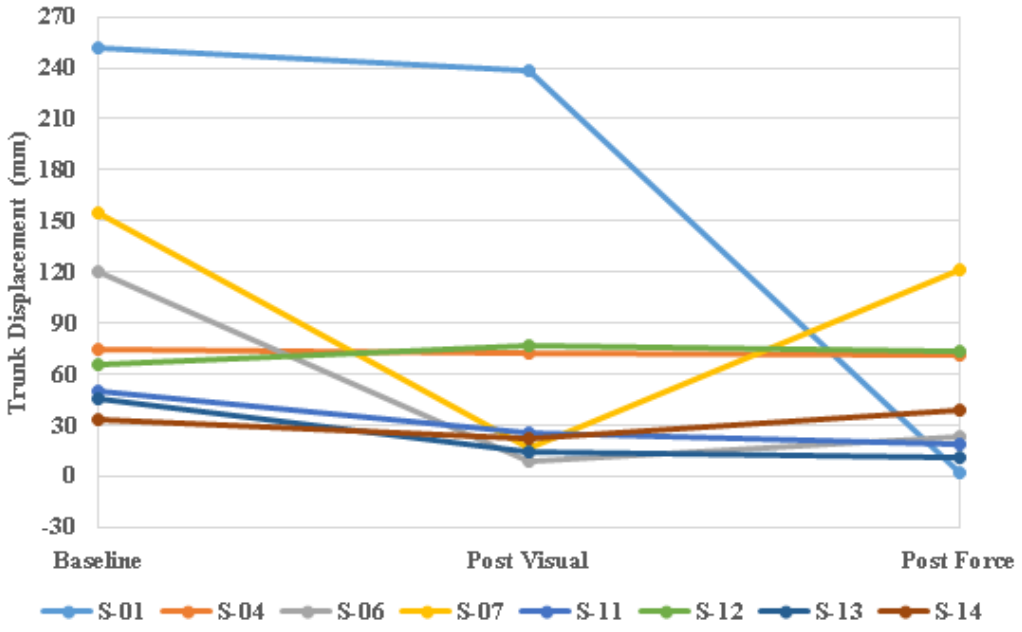


Figure 3.7 Individual results for participants who started with visual feedback

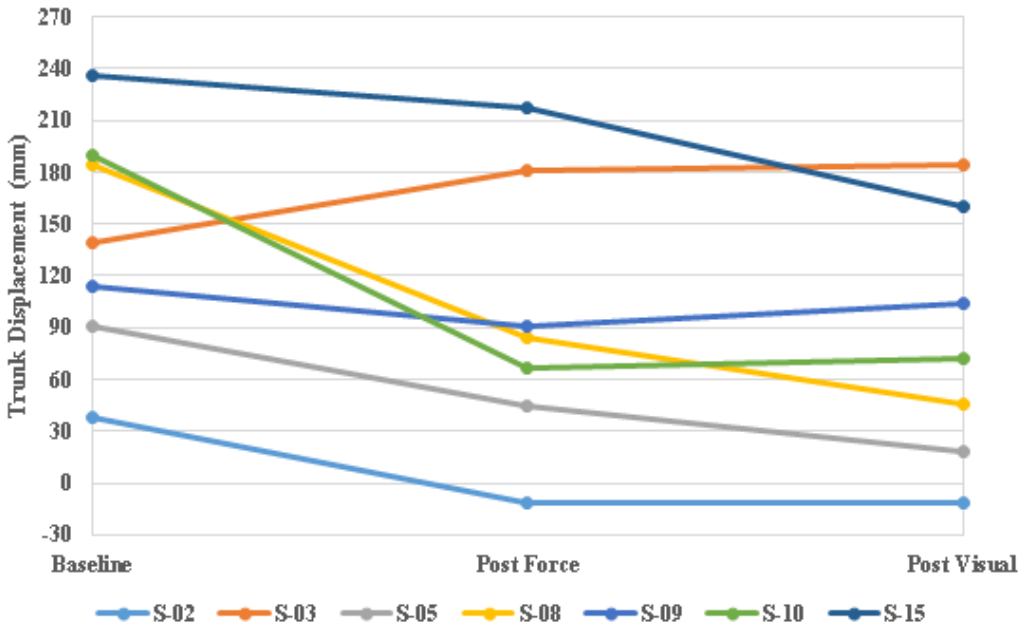


Figure 3.8 Individual results for participants who started with force feedback

Participants scored the usability of the system as "Good" (Average: 76(13)), according to the SUS.

3.4 Discussion

Both visual and force feedback decreased trunk compensation exhibited by stroke survivors after a session of reaching trials with augmented feedback provided in these modalities. When comparing force with visual feedback to reduce trunk compensation we did not find any significant differences. In addition, the data during the training trials (Appendix D) for most participants suggests that as soon as they received the trunk compensation information from either feedback source they were able to correct their movement, and the data did not follow a typical exponential adaptation curve [73]. Moreover, when asked if receiving visual or force feedback reduced how much they moved their trunk, the majority of participants agreed (93%

and 100%, respectively). This suggests that regardless of the modality of augmented feedback, participants use this information to correct their movement in a similar manner. However, studies with larger samples should be conducted to confirm this hypothesis. The question of which feedback medium is most effective for UE rehabilitation remains unanswered [74], [75]. These augmented feedback modalities offer advantages for unsupervised, remote, or intensive rehabilitation, as they do not require a therapist to physically restrain the individual or provide feedback in real-time; the system employed in this study was composed of commercially available products that could be integrated to provide rehabilitation outside of a research/rehabilitation setting. The lack of a physical constraint could provide additional benefits, as clients could make a conscious choice about controlling their trunk movement [17], which is something that a physical constraint could impede. With the physical guidance provided by the trunk restraints, the clients might not actively plan/program their trunk movements, which could inhibit important efferent and afferent information necessary for creating the internal models of the movement [18].

The augmented feedback utilized in this study has the potential to be provided at different frequencies during UE rehabilitation exercises, offering a variable schedule of reinforcement. Inversely, the continuous nature of the feedback provided by trunk restraints could be detrimental for motor learning; the "guidance hypothesis" states that practicing movements with constant feedback can make the participant dependent on the feedback, hindering independence [20]. However, for stroke survivors who show severe motor impairment with nonexistent trunk control, trunk restraint might be the only safe and viable option. As these individuals recover trunk control, and internal representations of movement are acquired, rehabilitation should move

toward augmented feedback exercises, progressing to an eventual removal of feedback in a graded manner.

In our study, six participants with greater UE motor impairment (FM ≤ 38) struggled to complete the force feedback condition due to UE weakness. These participants' affected hands had to be strapped, taped, or supported with a wrist brace, to hold onto the robots' handles or/and keep their wrist in a neutral position while they pushed through the force. Conversely, there were participants who found visual feedback less helpful, as it was easier to ignore, did not add any resistance to the movement, or was harder to understand. In the post-test questionnaire, 46% of participants responded that they would prefer to receive both feedback conditions, 27% only visual, and 27% only force. These observations, combined with the finding that there was not a statistical difference between employing visual or force feedback, suggest that there may not be an "ideal" feedback modality that works for every stroke survivor. We should instead use technology to provide feedback in an individualized manner, working to find the most suitable modality for an individual's impairment level, recovery stage, and learning style. Moreover, varying or combining the feedback media in different ways could be most effective for rehabilitation. By varying feedback type throughout exercises, we could prevent clients from relying on a particular source of information to correct their movements. Varying feedback in a random schedule ensures novelty, which is important for retention and transfer of motor learning [76]. Gaming rehabilitation systems show great potential, as they can provide feedback through different modalities [41]. In addition, the setting in which rehabilitation occurs should be considered, as visual feedback could be easier and more cost-effective to implement using devices that are already available in the home (i.e., television, computer monitor), and force

feedback may be more suitable in clinics or hospitals where larger, more costly devices can be acquired.

In this study, we did not investigate whether a simple verbal instruction to avoid compensatory movements would effectively decrease compensation. To mitigate this limitation, we employed the same number of repetitions (60) and a similar experimental procedure as a previous stroke rehabilitation controlled trial [16], in which investigators compared a verbal instruction group vs. a trunk restraint group in a unimanual physical reach-to-grasp task. The number of participants (14) and the samples were similar; however, our participants were on average older and more impaired (FMA scores). The previous study found that verbal instructions did not reduce compensation, while trunk restraint did. Our percent change values for visual (-41%) and force (-42%) feedback were on average superior to their trunk restraint values by 10% and 11%, respectively, and by 31% and 32% when compared to their verbal control condition. These results suggest that on average, augmented visual and force feedback in a short-term intervention could provide similar results to trunk restraint, and superior results to verbal instructions. Moreover, a study investigating the use of visual feedback and operant conditioning in five video game rehabilitations sessions [29] reduced relative compensation (trunk lateral lean) compared with no feedback. Further, a longer-term (twelve sessions) bimanual/unimanual intervention [17] study investigating the use of auditory feedback vs. trunk restraint found both methods improved scores on the RPS, FMA, and the Wolf Motor Function Test [77]. Our results, combined with these previous studies, suggest that augmented feedback could be employed as a complement or substitute to trunk restraint.

3.4.1 Study Limitations

The current study investigated the effects of feedback in a single session. Longitudinal studies should be conducted to explore the long-term effects of this intervention type. As kinematic data alone are not sufficient to confirm the clinical utility of augmented feedback for rehabilitation, future studies should examine whether the changes in movement seen with these feedback modalities correlate with increased functional performance and independence with activities of daily living. Another limitation of our study was that the small sample size could have limited the power to detect statistically significant differences for the secondary outcome measures. In addition, our results had large standard deviations due to the heterogeneity of the sample in terms of motor function, as shown by the baseline FMA and RPS scores. Studies with larger samples would enable researchers to increase the power to detect differences, and to stratify participants to various groups based on motor impairment. This approach would allow to draw stronger conclusions about the effects of augmented feedback on stroke survivors with different motor/functional abilities. During the intervention, some participants could not complete the study due to low motor function, which impacts the generalizability of our results for severely affected stroke survivors. In our study, some participants had to employ a wrist brace and/or strap to hold onto the robotic arm. Future studies should investigate alternate approaches to secure the hands while minimizing any potential effects to the participants' reaching performance. Finally, the force feedback that participants received was sensed through their upper limbs while holding the device's handles, which limits the generalization of these results to one sensing area of the body. It should be investigated if providing the force feedback directly to the trunk through a mechanical or electrical device could result in improved results to the ones presented in this work.

3.5 Study 2 Conclusions

Both visual and force feedback appear to be effective candidates for reducing trunk compensation in motor rehabilitation. It remains to be established whether one of these feedback modalities is more efficacious. However, the current results suggest that using technology to provide real-time feedback that works best for each individual could be a more effective approach than finding one modality that works for all individuals, or levels of motor, sensory and cognitive impairment.

Chapter 4: Biofeedback vs. Game Scores for Reducing Trunk Compensation after Stroke: A Randomized Crossover Trial

4.1 Introduction

Compensatory strategies are commonly employed by stroke survivors to adapt to the loss of motor function. However, their long-term use can negatively impact recovery [2], [3], [1]. In this study, we focus on reducing trunk compensation, which is a movement frequently observed when people with hemiparesis reach forward [15], [61].

Over the past few decades, robotic devices, virtual environments, and serious games used in the context of rehabilitation have provided researchers and therapists with the opportunity to employ augmented feedback to promote changes in motor behavior [23], [27], [78]. However, little attention [17], [29], [79] has been given to the role of technology in the reduction of compensatory movements: one current therapeutic approach relies on the use of physical restraints (straps or custom harnesses) to secure a person to a chair [3].

In a previous study [79], we found that visual or force feedback was capable of promoting a reduction in trunk compensation. At the end of that intervention, a large proportion of participants expressed in a post-test questionnaire that they would like to receive both feedback conditions simultaneously, even though they only received each one alone during the trials. Some of the reasons participants provided were: it would be easier to get feedback from both sources, it would provide them with more information, and they understood both feedback

conditions equally. These results, in addition to the current unanswered question of which type and characteristics of feedback are optimal for motor learning [75], [80], guided the present work, in which we combined Visual+Force feedback to investigate their effect on trunk compensation. Furthermore, as video games offer the possibility to employ motivating and engaging environments in which rehabilitation could occur, and given that they have shown promise in improving health-related outcomes [27], [81], we wanted to investigate if adding game scores to a virtual reaching task would provide any benefit when compared to just providing biofeedback about trunk compensation in a single training session.

The research questions we investigated in this work were: Will the use of Scores+Visual+Force feedback, and the use of Visual+Force feedback without Scores, reduce trunk compensation?; Will one of these feedback modalities be more effective than the other in reducing trunk compensation?

4.2 Methods

4.2.1 Participants

Fourteen participants (Table 4.1) were recruited from the community, stroke recovery groups, clinics, hospitals, and from a list of participants of a previous phase of this study [79]. The previous study was a single session conducted seven months before the work presented here. As a result, we were not expecting to find any long-term and/or memory (recollection of performing a similar study) effects that could affect the results of this intervention. This was confirmed by a statistical test ($t(8)=0.124$, $p=0.904$) of the baseline measurements of both phases (no difference), and by the fact that both feedback conditions reduced trunk compensation in our current study.

Enrollment, randomization, and assignment to interventions were conducted by the author (Figure 4.1). Participants were not aware of their allocation until after the baseline trials were completed. The sample size was based on two previous short-term interventions that focused on strategies to reduce trunk compensation [16], [79]. All participants provided written consent (Appendix A.3), and the study was approved by the university's Clinical Research Ethics Board.

Table 4.1 Demographic and clinical data for stroke participants

	Sex	Age (years)	Height (cm)	DHBS	PS	Type of Stroke	TSS (months)	FMA (max. 66)	RPS (max. 36)
S-01[a]	M	69	168	R	L	I	60	36	24
S-02[a]	M	48	170	L	L	I	38	32	17
S-03[a]	F	59	156	R	R	I	180	31	11
S-04[a]	M	65	170	R	R	I	144	40	28
S-05[a]	F	55	163	R	L	I	73	49	34
S-06[a]	M	63	178	R	R	I	29	58	33
S-07[a]	F	46	172	R	L	I	22	58	36
S-08[a]	M	70	175	R	R	I	109	23	8
S-09[a]	M	59	180	R	R	H	33	29	17
S-10	M	64	161	R	R	NP	6	14	1
S-11	F	36	150	R	L	I	301	29	18
S-12	F	53	156	R	L	I	73	35	25
S-13	F	65	152	R	L	I	72	16	7
S-14	M	59	168	R	R	H	44	21	10
Average		**57.9**	**165.6**				**84.6**	**33.6**	**19.2**
SD		**9.6**	**9.5**				**78.8**	**13.8**	**11.1**

[a] Participants who were part of a previous phase of this study. DHBS: Dominant hand before stroke, F: Female, FMA: Fugl-Meyer Assessment, H: Hemorrhagic, I: Ischemic, L: Left, M: Male, NP: Not provided, PS: Paretic side, R: Right, RPS: Reaching Performance Scale, TSS: Time since stroke, UE: Upper Extremity.

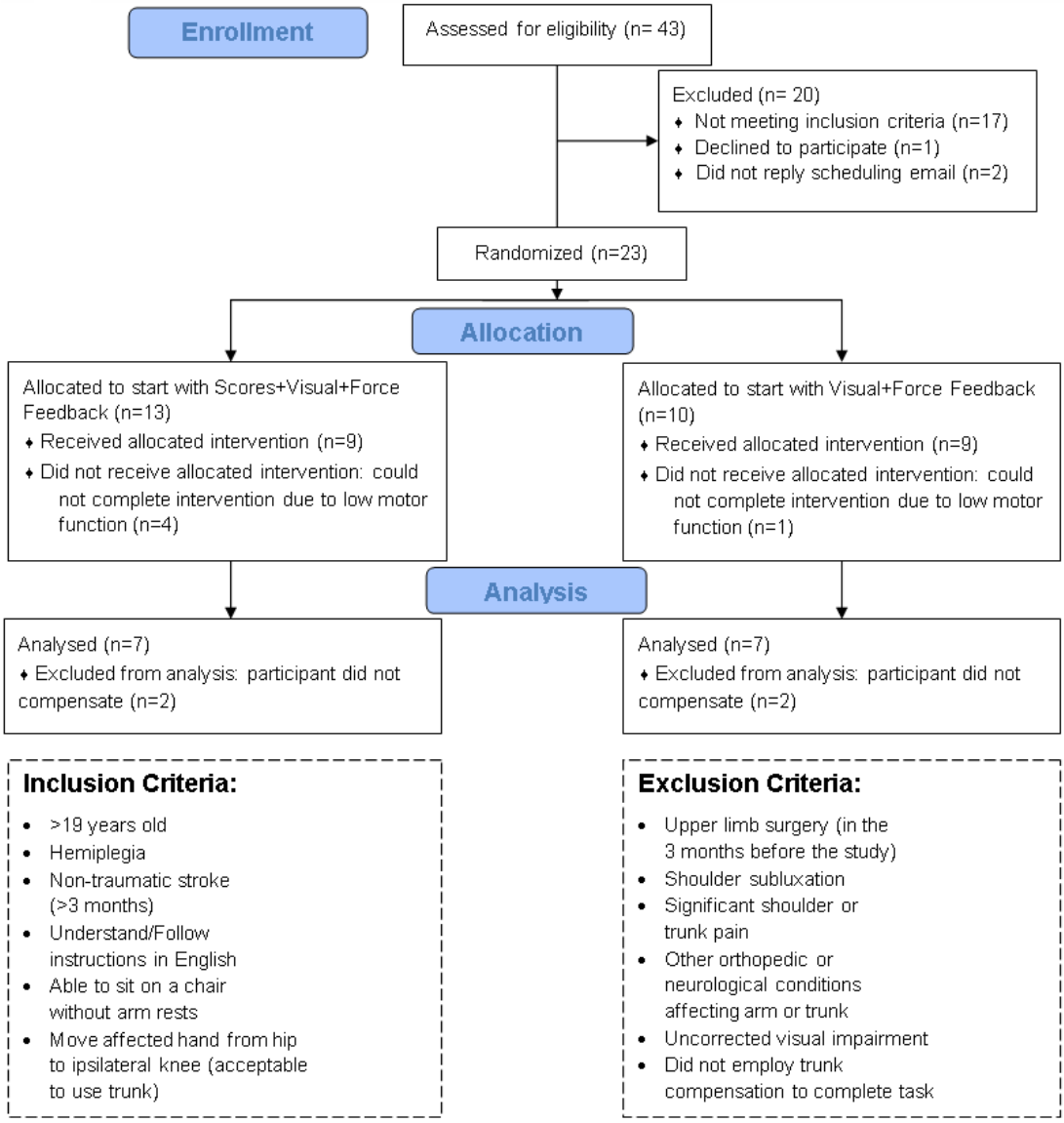


Figure 4.1 Recruitment and allocation

4.2.2 Clinical Assessment

The Upper Extremity Fugl-Meyer Assessment [82] (FMA) (Appendix B.2) was administered to measure motor impairment. In addition, the Reaching Performance Scale [65] (RPS) (Appendix B.3) was employed to measure trunk compensation. Both scales were administered by registered

occupational therapists at baseline (Table 4.1), which were blinded to the allocation of participants.

4.2.3 Experimental Design and Randomization

The study followed a crossover design (Figure 4.2) in which all participants experienced both feedback conditions (Scores+Visual+Force Feedback and Visual+Force Feedback). Participants were stratified based on Fugl-Meyer Assessment (FMA) upper-extremity scores (>=50 mild, <50 moderate to severe [10], [67]) to ensure group balance, and blocked randomized (block size: 2, computerized pseudo-random number generator [66]) to start with either feedback condition (Figure 4.2).

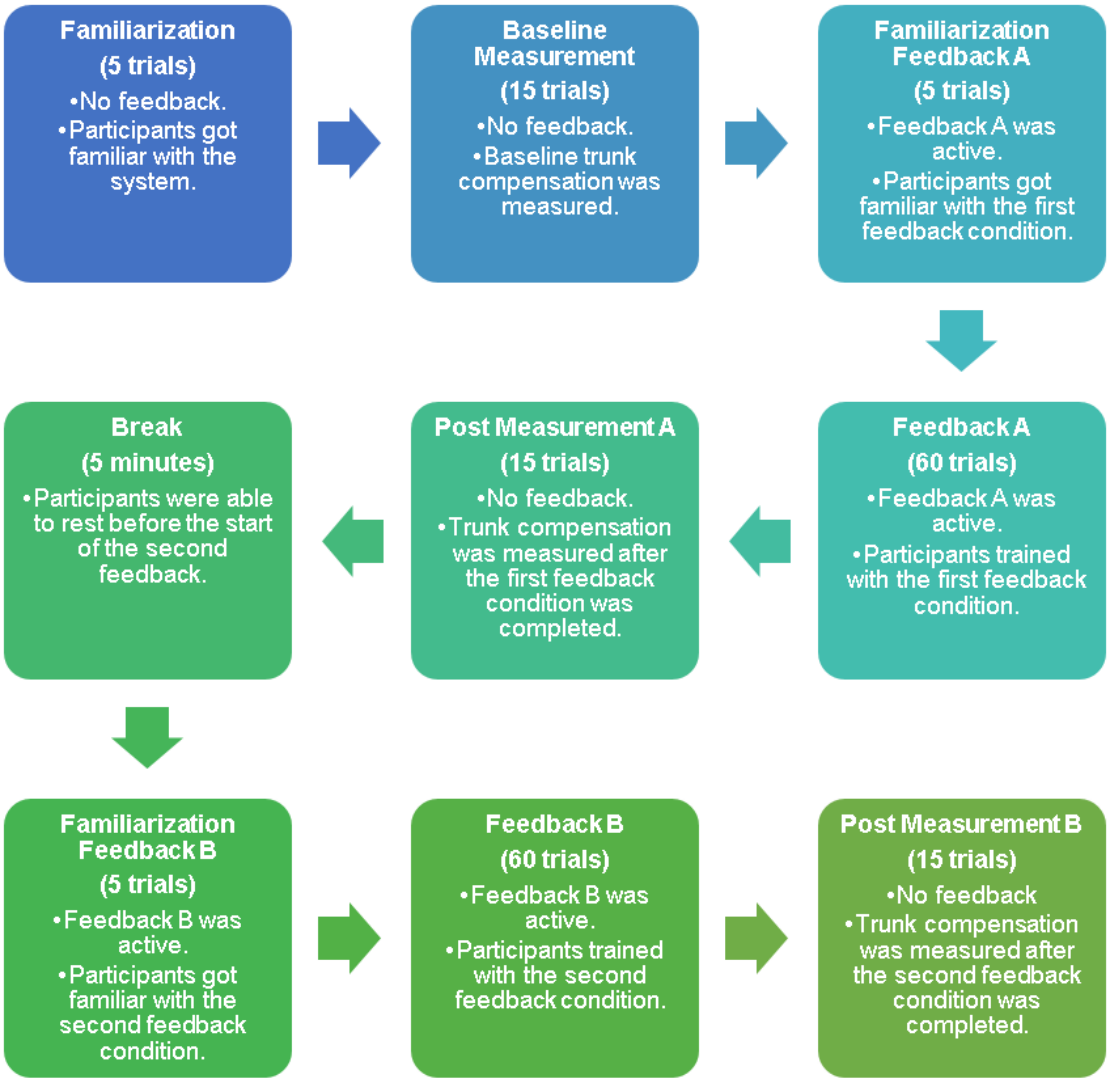


Figure 4.2 Experimental design

After the baseline measurements, participants were randomized to start with either Scores+Visual+Force or Visual+Force feedback. This was a low-risk study, with fatigue being the only potential harm. To reduce fatigue, participants received a 1 minute rest every 15 trials. In addition, participants were allowed to take breaks when they requested.

4.2.4 Experimental Setup

The system (Figure 4.3, left) included a Kinect v2 (Microsoft Corporation, Redmond, WA, USA) motion tracking camera, and two Jaco v2 (Kinova Robotics, Boisbriand, QC, Canada) robotic arms. The devices were connected and controlled by a desktop computer running LabVIEW 2014 (National Instruments Corporation, Austin, TX, USA), which displayed the reaching task on a monitor in front of the participant. In addition, an extra monitor, only visible to the research team, was used to supervise the system's inputs and outputs. The custom program employed libraries from the Haro3D Toolkit [68].

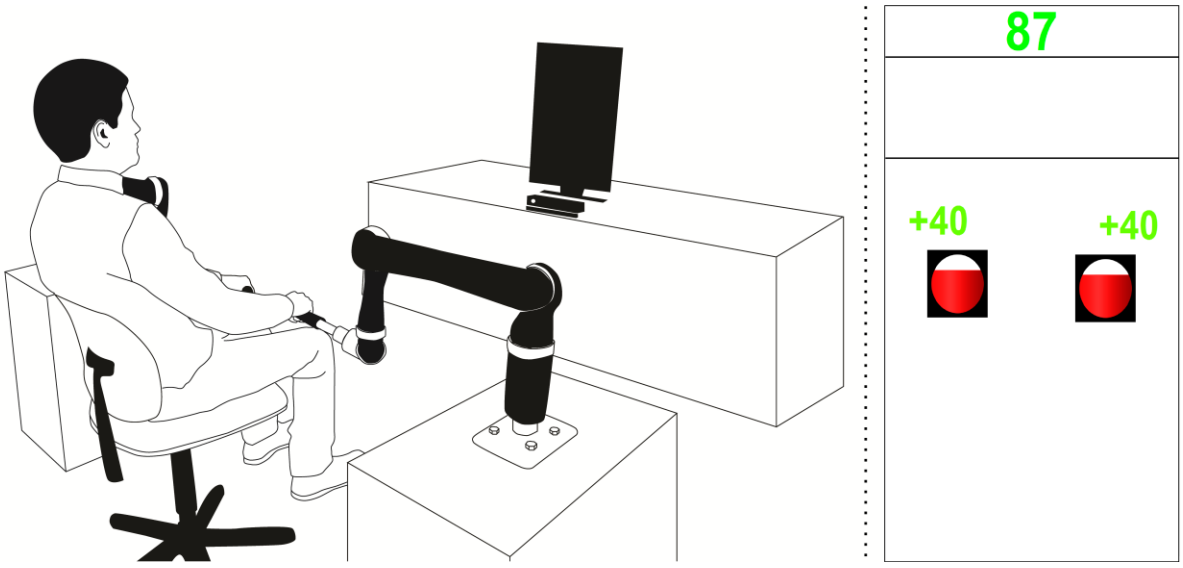


Figure 4.3 Experimental setup (left) and task (right)

Left Panel: Two robotic arms were used to interact with the system and to provide force feedback to participants. A computer monitor displayed the reaching task, visual feedback, and scores. A motion tracking camera captured the participants' trunk compensation.

Right Panel: The two lines at the top of the figure are the target boundaries. Each cursor represented one of the participants' hands. The fill level (visual feedback) inside the cursors represented the level of trunk compensation. The total score was displayed at the top of the screen; in-session scores were shown just above the cursors for one second.

4.2.5 Experimental Task

Participants held onto the handles of two robotic devices, while seated on a chair (Figure 4.3, left) with a height-adjustable footrest (knees at 90°). Before the start of the reaching trials, an initial position was calibrated, with participants seated in an upright position (trunk against the backrest) and their hands close to their hips. This position was used to ensure consistency of the starting point for all reaching movements. In addition, participants were asked to move their unaffected arm from their hips to their ipsilateral knee. 90% of this measured distance was set as the required distance for the reaching task.

The complete the task, participants were instructed to move both hands at the same time and in the same direction from their hips to their knees. The hands' forward/backward movements were translated to cursors' movements on the screen (Figure 4.3, right). The two cursors (one for each hand) had to be placed inside two target lines, and be kept in that position for one second. After each trial was completed, a new screen was presented to help participants move back to their initial position. When the feedback was off or when participants were not compensating, the robotic devices were free to move and did not apply any resistance to the participants' movements.

The level of all feedback conditions was proportional to the amount of trunk compensation captured by the motion tracking camera. For the first 30 mm of trunk compensation no feedback was activated, as these values were considered to be inside the threshold of "healthy" compensation [61]. Above that threshold, the feedback followed a linear relation with the amount of trunk compensation. The maximum feedback was set to be provided at 50% of the

exhibited trunk compensation during the baseline trials. This desired improvement in trunk compensation was considered to be adequate for a short-term intervention [79]. However, in longer studies (several days/weeks), this value could be adjusted after every session to accommodate for any continuous improvement/decline in participants' motor function.

Visual feedback was represented by an increase in the cursors' fill level (Figure 4.3, right), with more "ink" present in the circles when more compensation was exhibited. This feedback was selected for its simplicity, and because participants were likely already familiar with this type of representation for the level of common variables (e.g., car fuel and battery indicators).

Force feedback was provided as an increase in the required minimum force to move the robots, which acted as a cue to make users aware of their compensation. When no compensation was present, the robots were free to move: as participants started compensating they would need to apply larger forces to move in the forward direction. The maximum force feedback was set to the robots' maximum torque limit (9.5 Nm). If required, the maximum value was reduced if participants were not capable of moving the robotic devices when exhibiting maximum compensation during the familiarization trials. This strategy ensured that all participants were capable of reaching the target, even when they compensated. During the familiarization trials, all participants confirmed that they could sense the change in force when they compensated.

When the scores were active, participants gained points by moving both hands forward without trunk compensation. To ensure that participants were rewarded by exhibiting a positive behavior (no compensation) throughout the reaching task, they were able to collect points at four different

stages when moving towards the target. At each stage they were able to collect a maximum of one hundred points. In addition, an extra one hundred points were awarded when participants completed the reaching movement (regardless of compensation) to avoid users getting zero points in any trial. These extra points were implemented to handle failure (not able to reduce compensation in a specific trial) in a positive way [83], which could reduce the chances of participants' discouragement and diminished motivation due to the lack of accumulated points, especially in individuals with lower motor function. During the familiarization trials, all participants were informed of how the scoring system worked.

4.2.6 Data Analysis

The main outcome measure was trunk compensation, defined as the anterior displacement of the Kinect's shoulder-spine joint. Secondary outcome measures included: Trunk Rotation: angle between the shoulder joints and the frontal plane; Time: measured from the moment the target was presented to the completion of the reaching trial; Index of Curvature: straightness of the path taken by the hands to reach the target (ratio between path taken and a straight line); Root Mean Square (RMS) Error: measure of bimanual symmetry calculated by subtracting the distance between the hands' positions on every captured frame. All variables were measured at baseline and in post trials (Figure 4.2).

The motion data were filtered to remove inaccurate measured positions when any of the joints did not have a "tracked" state, as indicated by the Kinect's motion log. In addition, the data was resampled at 20 Hz, and a 6 Hz, fourth-order, zero-lag Butterworth filter was applied.

A post-test questionnaire (Appendix E.1) that asked participants about their experience with the task, feedback modalities and experimental system was administered at the end of the session. The questionnaire consisted of Likert items and open-ended questions. In addition, the System Usability Scale [72] (SUS) was used to assess participants' opinions of the system. Although the scores in the SUS range from 0-100, they are not percentages, and a value of 68 is considered above average [84]. The following adjectives have been suggested to interpret the scale [85]: "Worst Imaginable" (<38), "Poor" (39-51), "OK" (52-71), "Good" (72-84), "Excellent" (85-99), and "Best Imaginable" (100).

4.2.7 Statistical Analysis

To investigate if either one of the feedback conditions improved the kinematic variables from baseline, a one-sample t-test was conducted on the percentage change from baseline against a mean value of 0. To compare if one feedback condition was superior to the other one, an Analysis of Covariance (ANCOVA) was employed with a between-factor of group (start with either feedback condition) and a within-factor of treatment (Scores+Visual+Force and Visual+Force Feedback). Cohen's *d* was used as a measure of effect size [43]. A 95% Confidence Interval (CI) was calculated for significant results. Bonferroni-Holm correction [46] was used for post-hoc tests. Where violations to statistical model assumptions occurred, less restrictive models were employed to corroborate the results (Mixed ANOVA, Mann-Whitney U Test, and Sign Test).

In addition to examining the percentages of responses for each Likert item in the post-test questionnaire, Likert Scales (several questions examining the same underlying belief) were analyzed using a t-test against a neutral response (neither agree nor disagree).

4.3 Results

For the primary outcome measure, both feedback conditions were capable of reducing trunk compensation from baseline (Figure 4.4 and Table 4.2, right). However, the secondary outcome measures did not reach a statistically significant change.

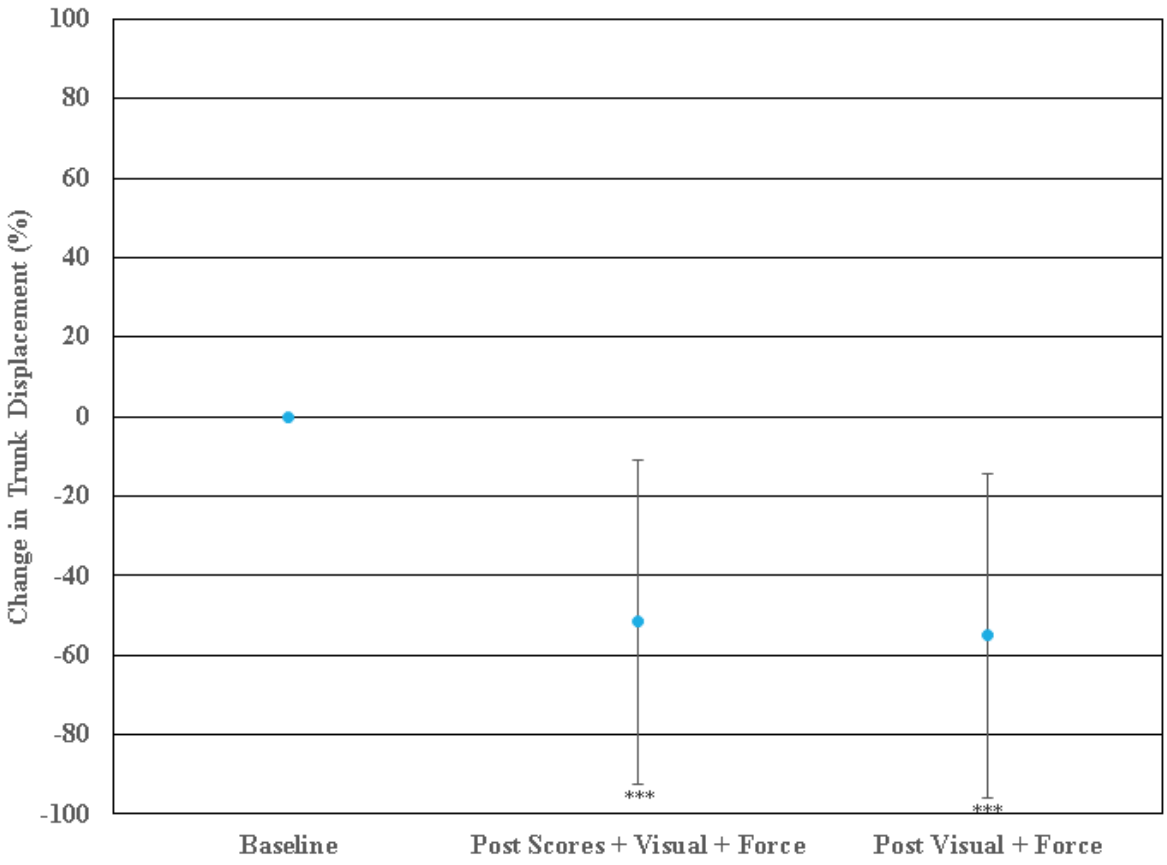


Figure 4.4 Trunk displacement percentage change from baseline to post measurements

Average values are presented with standard deviations indicated by error bars.

Table 4.2 Comparison between post scores+visual+force and post visual+force variables (left), percentage change from baseline to post measurements (right)

	Post SVF vs. Post VF		
	Baseline	**Post SVF**	**Post VF**
Trunk Displacement (mm)	101.4 (70.2)	55.1 (73.8)	51.6 (71.4)
Trunk Rotation (°)	0.97 (5.8)	-0.59 (6.6)	0.07 (6.3)
Time (s)	5.2 (1.3)	4.9 (1.7)	4.5 (0.99)
Index Curv. Left YZ	1.1 (0.21)	1.0 (0.1)	1.0 (0.14)
Index Curv. Right YZ	1.1 (0.33)	1.1 (0.13)	1.1 (0.13)
RMS Z (mm)	18 (9.0)	17.5 (7.6)	20.2 (12.3)
RMS Y (mm)	35.6 (15.7)	40.2 (23.6)	41.2 (20.8)

	Percentage change from Baseline to Post measurements	
	Post SVF	**Post VF**
Trunk Displacement (%)	**-51.7 (40.8)*** *t(13)=-4.73* *p=.000* *d=1.27* *CI: -75.2,-28.1***	**-55.2 (40.9)*** *t(13)=-5.05* *p=.000* *d=1.35* *CI: -78.8,-31.6***
Trunk Rotation (%)	-2.4 [-28.1, 97.9]	13.6 [-13.0, 77.2]
Time (%)	-4.7 (21.8)	-11.1 (18.1)
Index Curv. Left YZ (%)	0.83 [-5.1,5.3]	0.16 [-6.2,4.8]
Index Curv. Right YZ (%)	-0.83 [-4.98, 1.84]	-0.84 [-7.1, 1.7]
RMS Z (%)	-2.9 [-21.6, 31.6]	3.1 [-10.2, 24.4]
RMS Y (%)	20.4 [-34.5, 55.1]	14.5 [-21.8, 29.2]

Mean (SD). Median [1st and 3rd quartile]. Significant results are bolded (*p<.05, **p<.01, ***p<.001).
CI: 95% Confidence Interval. *d*: Cohen's d. *p*= p value. RMS: Root Mean Square. *t(degrees of freedom)*: t value.
SVF: Scores+Visual+Force Feedback. VF: Visual+Force Feedback.

When comparing which feedback condition was superior to the other one (Table 4.2, left), we did not find any statistically significant differences between employing Scores+Visual+Force and Visual+Force Feedback. Individual results are presented in Table 4.3, Figure 4.5, and Figure 4.6. Participants' trunk displacement data during the training trials are presented in Appendix F.

Table 4.3 Individual results for trunk compensation

	Baseline (mm)	Post SVF (mm)	Post VF (mm)
S-01	95.3	114.8	124.8
S-02[a]	127.0	25.2	22.6
S-03[a]	74.0	3.3	2.2
S-04	53.8	20.6	25.7
S-05	44.2	6.6	17.9
S-06[a]	98.0	33.8	27.2
S-07	41.4	35.3	4.6
S-08[a]	276.2	263.3	245.2
S-09	132.8	154.6	151.1
S-10[a]	60.9	37.4	40.8
S-11	70.1	27.7	26.6
S-12[a]	49.2	0.2	13.3
S-13	226.6	24.4	15.5
S-14[a]	70.1	24.5	5.3
Average	**101.4**	**55.1**	**51.6**
SD	**70.2**	**73.8**	**71.4**

[a] Participants who started with SVF. SVF: Scores+Visual+Force Feedback. VF: Visual+Force Feedback.

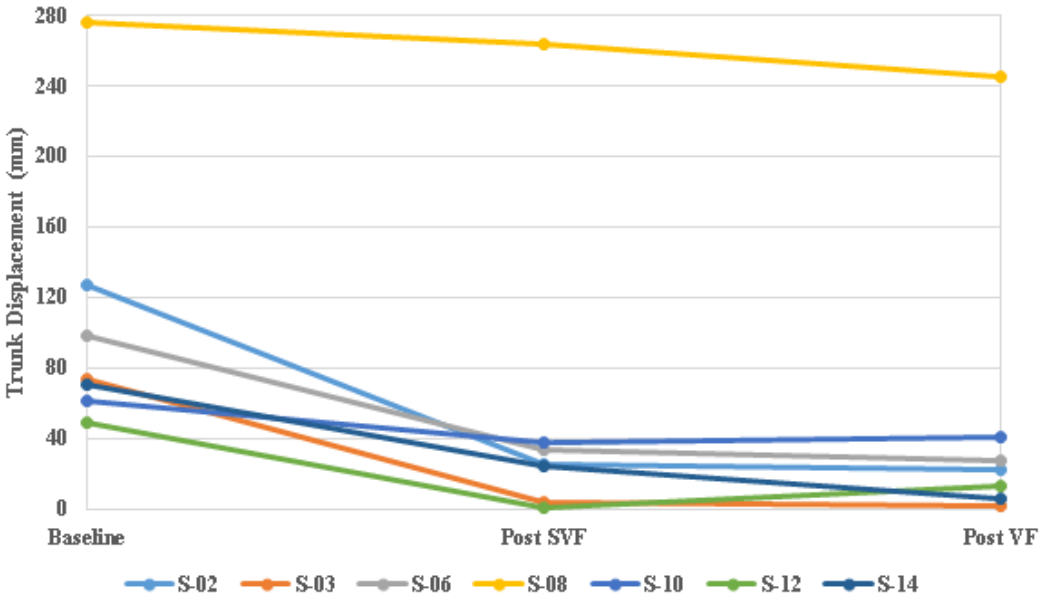


Figure 4.5 Individual results for participants who started with scores+visual+force feedback

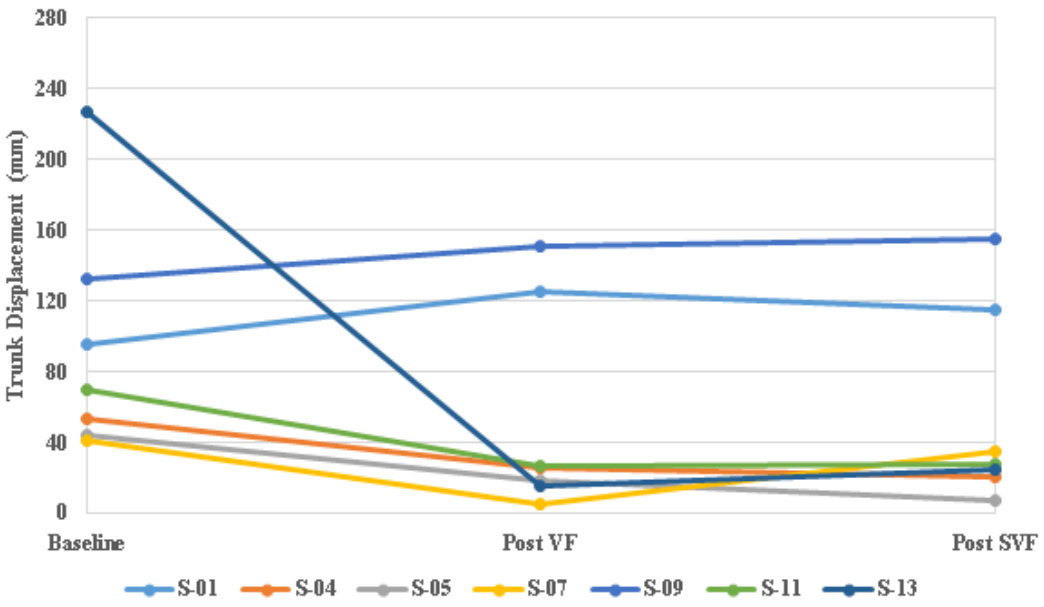


Figure 4.6 Individual results for participants who started with visual+force feedback

Figure 4.7 presents a selection of questions from the post-test questionnaire; remaining questions are presented in Appendix E.2. A mix of responses was obtained when participants were asked if they had moved their trunk to reach the targets (36% agree, 14% neutral, 50% disagree). When receiving either one of the feedback conditions, the majority (86%) of participants expressed that they reduced their trunk compensation. For almost all participants (93%), they would prefer to receive the Scores+Visual+Force feedback to reduce their trunk movement, as scores provided them with: motivation, a game-like presentation of the task, encouragement to do better based on previous scores, and the ability to compete.

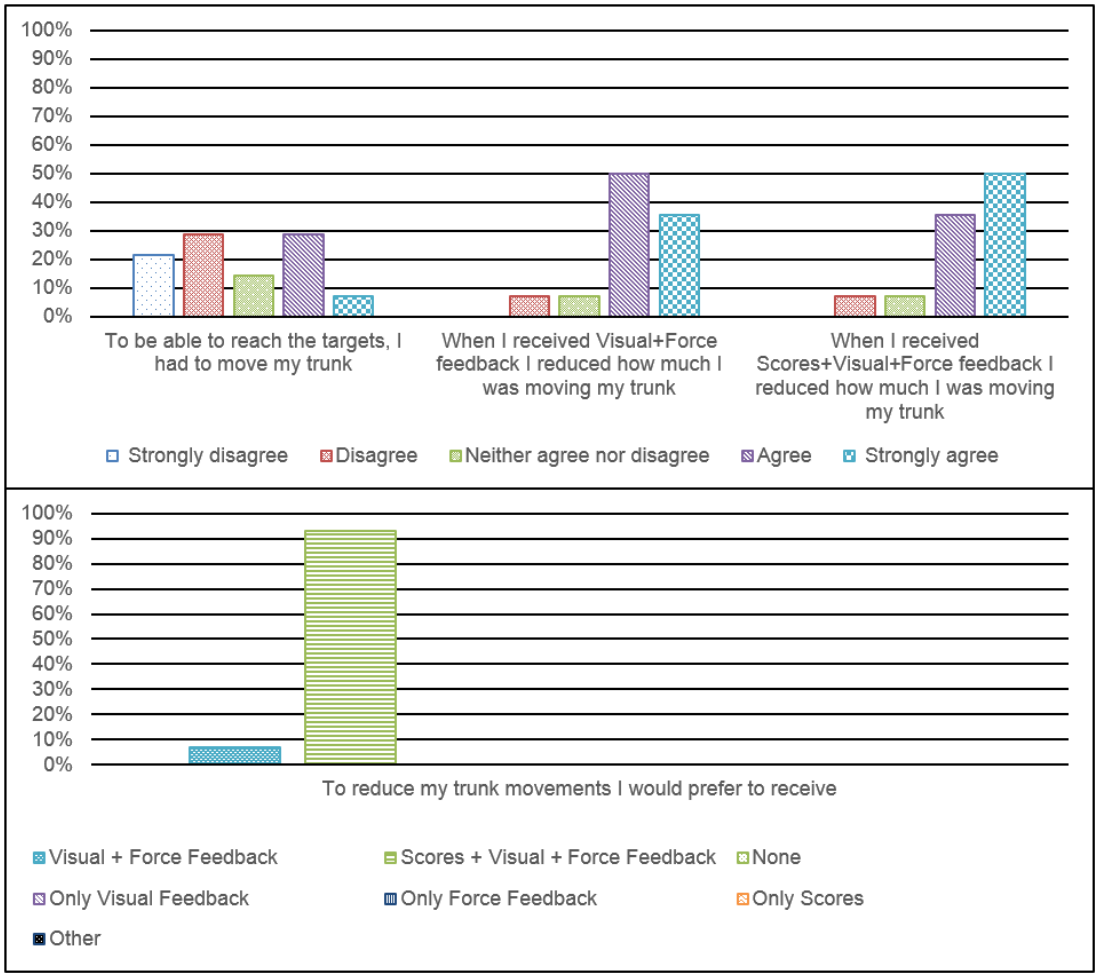


Figure 4.7 Post-test questionnaire selected results

Questionnaire was administered at the end of the intervention. The remaining questions are presented in Appendix E.2.

For the post-test questionnaire Likert scales, participants: agreed that the level of difficulty of the reaching task was adequate (Questions A.1-A.4, $t(13)=2.47$, $p=0.028$, $d= 0.66$, *95% CI*: 3.06-3.90), and agreed that the system was appropriate for performing reaching movements for rehabilitation (questions E.1-E.7, $t(13)=8.17$, $p=0.000$, $d=2.18$, *95% CI*: 3.79-4.35). For the individual Likert items, most people: disagreed that the feedbacks were difficult to understand (93% for both feedbacks), disagreed that the visual feedback (ink filling the cursor) and scores

were difficult to see (93% for both), and disagreed that the force was difficult to feel (79% for Scores+Visual+Force and 86% for Visual+Force feedback).

Participants scored the usability of the system as "Good" (Average: 73(15)), according to the SUS.

4.4 Discussion

Based on the anterior trunk displacement motion data, participants were capable of reducing their trunk compensation when provided with either Scores+Visual+Force or Visual+Force feedback. In addition, during the training trials most participants were able to correct their movements as soon as they received the trunk compensation information from either feedback source, and the data did not follow a typical exponential adaptation curve [73]. Moreover, in the post-test questionnaire, the majority of participants answered that they decreased their compensation levels when receiving either feedback condition. These results, in combination with our previous study [79], in which we found that force or visual feedback alone reduced trunk compensation, provide supporting evidence to the idea that regardless of the type of augmented feedback provided in a short-term intervention, participants are capable of modifying their movement strategies to reduce trunk compensation. As a result, it would appear that the information itself (real-time monitoring of trunk compensation) is more important than the medium employed to communicate the information. Moreover, our results reinforce the concept that stroke survivors might still have unexploited motor abilities that are masked by compensatory movements [14]. If we focus on reducing these compensatory strategies, we might be able to unmask the "correct" movement patterns needed for recovery. Furthermore, the monitoring of movement quality could

play an important role in stroke recovery rehabilitation, as sometimes improvements evaluated by clinical scales and brain imagining technologies can be the result of the use of compensatory movements and not of true recovery occurring at the neuronal level [1]. Employing quantitative kinematic analysis as a tool for rehabilitation professionals to obtain more detailed descriptions of the recovery process of their clients could be a significant complement to therapeutic practices that currently rely on qualitative ordinal scales [86]. Finally, investigating how brain activation patterns and cortical representations change as a result of compensatory reduction strategies might lead to a better understanding of the complex neuronal recovery process [15].

A similar short-term study [16], with the same number of training trials and participants per group, compared verbal instructions (directions not to move the trunk) versus employing trunk restraints. In the study, the verbal instructions condition did not reach statistical significance; on the other hand, the trunk restraints did. On average, our augmented feedback results were: superior to their verbal instruction condition and similar to the trunk restraint values. This is in agreement with the results of our previous study [79], in which only visual or force feedback were provided. Based on the aforementioned studies, it would appear that providing trunk compensation information as augmented feedback, which can track the performance of the user throughout the movement, could be superior to just providing verbal instructions to remind participants not to move their trunk, at least in a short-term intervention. In addition, the results support the idea that employing augmented feedback could provide similar results to the more restrictive trunk restraints. Longer studies with larger samples would need to confirm these results before making a final recommendation to the rehabilitation community.

One of the possible advantages of employing augmented feedback versus completely restraining the trunk movement of participants is that it would enable participants to be actively involved in the formulation of motion strategies and in the reception of afferent and efferent information derived from the movement, which are important factors for optimal motor learning [18]. In addition, the schedule and frequency of the feedback strategies we propose can easily be modified (software parameters) to avoid a detrimental reliance on the feedback (guidance hypothesis [20]). On the other hand, trunk restraints are always active, unless a therapist completely removes the straps. Nevertheless, trunk restraint might be the only feasible option for participants with significant motor impairment and complete lack of upper body motor control, for which reaching movements might be dangerous to perform without physical assistance. As these participants improve with time and training, they might be able to transfer to augmented feedback paradigms.

When comparing if adding scores provided any advantage to just employing biofeedback, we did not find any statistically significant difference. A similar result was obtained by Alankus et al. [29], as they could not find any difference between simple biofeedback (showing lateral trunk tilt in a rehabilitation game) versus providing/deducting points based on compensation; however, in their study only the scores condition resulted in a reduction of compensation when compared to a no feedback condition. The aforementioned results could suggest that in a short-term intervention, the positive effects that scores could have on participants' performance might not be greatly superior to just receiving biofeedback, at least for modifying trunk kinematic variables. Nonetheless, in the post-test questionnaire, 13/14 participants expressed that they would prefer to receive the scores together with biofeedback to reduce their trunk compensation.

Some of the reasons they mentioned were that the scores provided them with: motivation, encouragement to do better based on previous scores, a game-like presentation of the task, and the ability to compete. All of these elements might have a bigger role in long-term interventions where increased motivation and engagement become important factors to promote adherence to therapy programs [87]. In longer interventions, scores could be used to [88] show trends over several days or weeks and reward secondary actions (e.g., time playing the game, and improvements in other kinematic variables, besides trunk compensation).

One of the challenges in the design and provision of multimodal feedback is that the use of multiple sources of information could result in participants getting overwhelmed or confused [89]. In our study, we did not find that employing multiple strategies together was detrimental for kinematic performance. The effect sizes obtained when combining feedback types versus employing visual or force feedback alone [79] resulted in some small improvements: Scores+Visual+Force and Visual+Force were superior to providing only Visual feedback by +0.28 and +0.36, respectively, and when compared against Force feedback they were superior by +0.38 and +0.46. However, the motion of the virtual cursors was only in one plane, which was proportional to the movement of the participants' hands in the anterior/posterior direction, limiting the task complexity. It would be important to conduct studies in which participants move their upper limbs in all directions and play more elaborate games to confirm if the increase in task complexity does not lead to a detrimental effect of employing multimodal feedback.

Given that most participants agreed that: the level of difficulty for the reaching task was adequate, the system was appropriate for performing rehabilitation exercises, the feedbacks were

easy to understand and perceive, and that the system was "Good" in terms of usability (SUS), it would appear that a similar system could be employed for long-term interventions. Based on the evidence found in this study and our previous phase, we would recommend that rehabilitation professionals employ a single feedback or a combination that works best for each client's preferences and motor abilities, as all tested conditions seem to be capable of promoting a reduction in trunk compensation. The results of our current and past study could indicate that the use of larger robotic devices might not be completely necessary to obtain a reduction in trunk compensation (longer studies are needed to confirm this), which could be beneficial for participants, clinics, and hospitals with limited financial resources. We would recommend that future studies investigate if visual feedback combined with scores could obtain similar results to trunk restraints in a clinical environment over a period of several weeks. If superior or comparable results were to be obtained, an at-home rehabilitation program could be implemented at a low cost (all items are commercially available and affordable, e.g., Kinect camera, computer monitor or TV, and personal computer or laptop), which could provide participants with the opportunity to perform the high number of repetitions needed to promote neuroplastic changes in the brain, instead of the low number currently being provided in clinical settings [22]. In our study, participants with severe to mild motion impairments were capable of performing 180 upper limb functional repetitions in just one session.

4.4.1 Study Limitations

One of the end-goals of stroke rehabilitation is improving functional independence [59]. Consequently, longitudinal studies in which clinical scales (measuring function) are administered at different time points, in addition to kinematic variables assessing the quality of the exhibited

movements, should be conducted to fully confirm the effectiveness of the proposed augmented feedback strategies. In our study, we were not expecting to observe functional changes after a single session; however, after several weeks of training we would anticipate functional/impairment changes. Another limitation of the presented work was the small sample size, which resulted in large standard deviations for the kinematic variables that could have impacted the power to detect statistically significant differences for the secondary outcome measures. Larger samples of participants with different motor impairment levels should be included in future randomized controlled trials, and stratified according to baseline clinical scales. This strategy will ensure that researchers and rehabilitation professionals obtain a clearer picture of the role of feedback on participants with different functional levels. Finally, some participants could not complete the study due to low motor function, which impacts the generalizability of our results for severely affected stroke survivors.

4.5 Study 3 Conclusions

In a short-term study, multimodal augmented feedback provision (Scores+Visual+Force and Visual+Force feedback) about stroke survivors' trunk compensation levels resulted in a reduction of trunk displacement. No statistically significant difference was found to support that one feedback strategy was superior to the other one. However, most participants responded that they would like to receive game scores for reducing their trunk compensation. As a result, the potentially superior positive effects of including game scores might not have been observed in a short-term intervention. Longer studies should investigate if the use of game scores could result in trunk compensation improvements, especially when compared against trunk restraint strategies.

Chapter 5: Conclusions

Hemiparetic stroke survivors tend to use their trunk when reaching forward as a way of adapting for the loss of motor function in their upper extremities. Although these movements can help them regain some functional independence, their long-term use can have detrimental effects on their recovery. Even though compensatory trunk movements are common and have being investigated in the rehabilitation literature, the current therapeutic practice to reduce them rely on the use of straps and harnesses that physically restrict the movement of the user. Technology on the other hand can be employed to inform stroke survivors in real-time about their level of trunk compensation, and to actively involve the person in the decision to reduce these unwanted movements. However, there is a current gap in the literature on the use of technology to reduce trunk compensation. In an attempt to address this issue, this dissertation's goal was to explore if augmented feedback cues could be employed to reduce trunk compensation in stroke survivors.

This dissertation was divided into three studies that explored: how trunk displacement is employed by stroke survivors when reaching at different heights and distances (Chapter 2); if visual and force feedback could be used to reduce trunk compensation (Chapter 3); and if employing biofeedback alone could obtain different results to providing game scores for reducing trunk compensation (Chapter 4).

This dissertation contributes to the limited literature on employing augmented feedback for reducing trunk compensation, and provides motivation for further exploration of the role of technology and feedback in the realm of stroke rehabilitation. The contributions of this dissertation are listed below:

1. Phase 1: First study to investigate how stroke survivors' trunk compensation is affected by the height and distance to virtual targets in a bimanual reaching task.
2. Phase 2: First study to investigate the use of robot-mediated force feedback cues to reduce stroke survivors' trunk compensation.
3. Phase 2: First study to compare the use of visual vs. force feedback cues for reducing trunk compensation in stroke survivors.
4. Phase 3: First study to compare visual+force vs. scores+visual+force feedback cues to reduce stroke survivors' anterior trunk displacement.

The following sections (5.1-5.3) present a review of the key findings of this dissertation.

5.1 Does the Distance and Height to Targets Affect the Trunk Movements of Stroke Survivors?

The study presented in Chapter 2 investigated the effect of targets' distance and height on the trunk compensation of stroke survivors. The motivation for this study was that in activities of daily living people reach in a three dimensional space, and specifically, older adults (higher risk of stroke) tend to employ both hands [6]. However, the literature [2], [12], [14], [31] on compensatory movements have mainly focused on unimanual reaching and have given little attention to the effect of target height on trunk displacement.

In this study we found that the magnitude of trunk displacement in reaches to all heights and distances was larger in stroke survivors when compared to a control group. This result was consistent with unimanual [2], [14], [31] and bimanual [32] studies that investigated reaching movement at chest level. As a result, our study supports the idea that for targets placed at arm-reach distance, stroke survivors exhibit larger levels of trunk compensation regardless of the distance and height to the targets. Another finding was that the target that elicited the largest trunk compensation in stroke survivors was the one at waist level. We hypothesize that the main reason for this result was that participants could reach targets below chest height by only employing trunk flexion, which allowed them to complete the task with minimum use of their shoulder and elbow joints. A previous study on unimanual reaching on healthy participants obtained similar results [53], and our control group's results, before multiple-comparisons correction, also support this idea. Consequently, it would appear that both stroke survivors and healthy controls employ similar trunk movement strategies when reaching downwards, however, the magnitude of the compensation is larger for the stroke survivors. Finally, the targets at shoulder height represented a bigger challenge (longer times and paths) to stroke survivors than the ones placed at chest height. This observation could be the result of the reduced range of motion that hemiparetic stroke survivors face when having to move outside of the flexor synergy to reach upwards [57].

The results from this study support the idea that stroke survivors employ different reaching strategies when moving towards targets at different heights. As daily tasks are performed in a three-dimensional space, the results from this study are important for rehabilitation professionals and researchers who want to promote functional independence in their clients/participants.

Moreover, newer rehabilitation technologies that employ virtual simulations of daily tasks should take into consideration the different movement patterns that people exhibit at different heights to be able to set adequate kinematic goals in their virtual environments.

5.2 Could Visual and Force Feedback Cues Reduce Stroke Survivors' Trunk Compensation?

After obtaining a better understanding of how people reach and compensate when performing bimanual reaching movements (Chapter 2), we proceeded to investigate if augmented feedback could be employed to reduce stroke survivors' trunk compensation. Some of the main reasons for performing this study were that there was a gap in the literature on the topic of employing augmented feedback for reducing trunk compensation [29], [90], [91], and that current therapeutic strategies only relied on the use of physical restraints [3], [92].

In the study we found that providing information about the level of trunk compensation in the form of real-time visual (through a monitor) or force (through robotic devices) feedback resulted in a reduction of this movement. This result was obtained from the trunk kinematic data, and was also confirmed by participants in an exit questionnaire. Employing augmented feedback methods such as the ones tested in the study could provide advantages over physical restraints, as the person could make a conscious choice to avoid trunk use [17], and the frequency and intensity of the feedback could be easily adapted to each person's abilities and recovery process. In addition, employing these non-restrictive feedback modalities could result in the person receiving afferent and efferent information that is important for motor learning [18], and its

varying frequency and schedule could ensure novelty and reduce the chances of people relying on the feedback [20], which are key factors in the retention and transfer of motor skills [76].

When comparing if one feedback methodology was better than the other, we did not find any statistical evidence to support this idea. Consequently, the question of which feedback condition is more effective remains unanswered [74], [75]. As both feedback conditions worked to reduce trunk compensation, it would appear that employing an affordable and readily available computer or TV screen might be sufficient to provide feedback about trunk compensation instead of having to use more complex and expensive robotic devices. However, longer studies should be performed to confirm this result. Finally, when asked which feedback condition they would prefer to receive, a large proportion of participants said both, which guided the decision to combine two feedback conditions in the last phase of this work (Chapter 4).

5.3 Does Adding Game Scores to a Virtual Reaching Task Result in a Larger Reduction of Trunk Compensation when Compared to Biofeedback Alone?

Given that participants expressed interest in receiving both feedback conditions for reducing trunk compensation (Chapter 3), we decided to explore how the combination of visual and force feedback could change the compensatory behavior of stroke survivors. In addition, as engaging and motivating video games have the potential to be employed to improve health-related outcomes [27], [81], we investigated if adding game-like scores to the reaching task would result in improved results when compared to just providing biofeedback about trunk compensation.

In this study, both the game scores and biofeedback conditions reduced trunk compensation, which was confirmed by both the kinematic data and the exit questionnaire. Moreover, when comparing our results against a previous study [16], which explored the use of verbal instructions vs. employing trunk restraints to reduce compensation, we found that our values were similar to their trunk restraints results and superior to their verbal instructions condition. This same outcome was observed in our previous study (Chapter 3). These combined results provide support to the use of augmented feedback for reducing trunk compensation, and to the idea that regardless of the source of the real-time performance feedback, participants appear to be able to reduce their levels of trunk compensation. Moreover, in our studies we have provided evidence to support the concept that stroke survivors might still have motor capabilities that are masked by the use of compensatory strategies [14]. As such, employing technology to provide quantitative feedback about the quality of stroke survivors' movements appears to be a promising strategy to discern differences between true motor recovery and compensation, and to complement current qualitative clinical assessment scales.

Employing the game scores in addition to the provided biofeedback did not result in a larger reduction of the targeted compensatory movement. A similar result was observed in a previous study [29] that investigated trunk lateral lean in the stroke population. Consequently, it would appear that including game scores in a short-term trial does not elicit any added benefits when compared to just providing biofeedback. However, the majority of participants expressed that they would prefer to receive the game scores in addition to the biofeedback to reduce their trunk compensation. This could suggest that the potential positive aspects of employing game scores in a rehabilitation task could have a larger role in longer interventions. As both motivation and

engagement are important factors for the adherence to therapy programs [87], participants might be more inclined to receive in-game rewards to comply with long and arduous rehabilitation interventions. As such, longer studies that explore the role of game scores in the reduction of trunk compensation should be performed before arriving to a final conclusion.

5.4 Recommendations and Future Work

Given that the three phases of this work included small sample sizes and were conducted during a single session, we would recommend that future studies with larger samples concentrate on the long-term application of the concepts that we have presented in this dissertation.

To assess the motor learning of a new skill, its retention and transfer needs to be evaluated [76]. As a result, we would recommended that future projects measure the retention of reduced trunk compensation after several weeks or months, and evaluate its transfer by providing participants with tasks that are different from the one employed during training. In addition, as one of the major goals of rehabilitation technology is to be able to promote functional recovery, we advocate for the use of clinical functional scales to investigate if the kinematic improvements are translated into functional gains. In our studies, we were not expecting to see any functional changes after only one session of reaching movements; as such we only employed clinical scales at baseline. However, future long-term projects will need to provide supporting evidence from currently employed measurement tools before a recommendation to change current practices can be made to rehabilitation professionals.

At the end of the research studies presented in this work, an end-of-project series of talks was given to disseminate the results of this dissertation amongst stroke survivors (Douglas Park, North Shore, and South Burnaby stroke recovery groups) and rehabilitation professionals (Abilities Neurological Rehabilitation Clinic Surrey). The presentation slides are part of the online supplementary material of this dissertation. After the presentations, attendees (31 stroke survivors, and 7 rehabilitation professionals) answered a short questionnaire (Appendix G) to provide their feedback about the presented rehabilitation system and help guide future work for this project. For therapists, some of the most frequent responses for their desired features in a technology based rehabilitation system were ease of use and affordability. For stroke survivors, they were: use of system leads to improvement, system provides feedback, receiving scores, affordable, available, ease of use, and help with arm and hand movements.

In our results we found that no feedback modality or combination was superior any other. Consequently, given that one of the main concerns of therapists and stroke survivors appears to be the affordability of the system, we would recommend that future long-term interventions employ visual feedback and game scores to provide information about trunk movements. Employing visual feedback would allow therapists and clients to employ technology (televisions or computer screens) that is readily available in clinical and home environments. In addition, the frequently mentioned concern of having systems that lead to motor and functional improvements reinforces the need for transferring the ideas and lessons learned from this dissertation to longer interventions in which researchers can provide evidence of clinically significant changes in activity and functional scales. Lastly, the ease of use of the system should be considered before taking a step forward into the commercialization of the presented work. For the system to be

successfully adopted by rehabilitation professionals and their clients, we would need to ensure that the required steps to set up the system are minimized and that the complexity of the software and hardware are reduced, while providing an engaging and motivating environment for stroke survivors to rehabilitate.

The work presented in this dissertation supports the idea of employing technology to provide real-time feedback to rehabilitating stroke survivors. The information that was gathered in the different studies will provide supporting evidence for future research in which the use of augmented feedback is used for modifying the motor behavior of people with disabilities. Moving forward, we hope that in the next decades the use of technology becomes an essential part of the assessment and treatment of not only stroke survivors but all persons needing to improve their motor skills.

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Appendix A Consent Forms

This appendix presents the consent forms from the different research studies.

A.1 Chapter 2 Consent Form

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Mechanical Engineering

Informed Consent Form: Stroke Survivors

RIS:
Reaching in Stroke

Principal Investigator
Name: Hendrik F. Machiel (Mike) Van der Loos
Position title: Associate Professor
Organization: UBC Department of Mechanical Engineering

Co-Applicants
Name: Bulmaro A. Valdés Benavides
Position title: PhD Candidate
Organization: UBC Biomedical Engineering Program

Contact Person:
Please contact Bulmaro Valdés or Hendrik F. Machiel (Mike) Van der Loos, in the event of any unusual occurrences or difficulties related to this research.

Funding Agency
The Peter Wall Solutions Initiative (PWSI) of the Peter Wall Endowment at UBC is funding this study. Information on this funding initiative can be found at: http://research.ubc.ca/vpri/ubc-peter-wall-solutions-initiative

Usability Testing

Introduction

We invite you to take part in a research study being conducted by Mike Van der Loos, who is a professor at the University of British Columbia, and his colleagues. Your participation in this study is voluntary and you may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study will likely not benefit you directly, but we might learn things that will benefit others. You should discuss any questions you have about this study with Dr. Van der Loos or the other investigators present.

Your Participation is voluntary

Your participation is voluntary. You have the right to refuse to participate in this study. If you decide to participate, you may still choose to withdraw from the study at any time without any negative consequences to the medical care, education, or other services to which you are entitled or are presently receiving.

You should be aware that there is a difference for both you and your doctor between being a patient and being a research participant. As a patient all medical procedures and treatments are carried out for your benefit only according to standard accepted practice. As a research participant you and your doctor also must take into account the requirements for the research study. These may include procedures and treatments that are not part of standard practice or are not yet proven. This consent form describes the diagnostic and treatment procedures that are being carried out for research purposes. Please review the consent document carefully when deciding whether or not you wish to be part of the research and sign this consent only if you accept being a research participant.

If you wish to participate in this study, you will be asked to sign this form.
Please take time to read the following information carefully and to discuss it with your family, friends, and doctor before you decide.

Purpose of the Study

The purpose of this study is to investigate the bimanual reaching movements of stroke survivors and healthy adults. We propose to use a motion tracking camera (Microsoft Kinect) and two haptic robotic devices (Geomagic Phantom) to obtain information about the way the users' hands and bodies move in space when they reach forward with both hands.

We will use the results from this study to develop systems that will focus on the quality of the movements of stroke survivors when they rehabilitate at home using commercially available technology.

Study Design

In this study, we will ask you to perform a set of forward reaching movements while holding two small robotic devices in your hands (Figure 1). At the same time a motion tracking camera will be analyzing the movement of your body while you perform the reaching activities (Figure 2). During the session, you will be seated in an office chair without armrests. All the motors of the robotic devices will be turned off and no forces will be applied on you, we will only use these devices to measure the position of your hands in space.

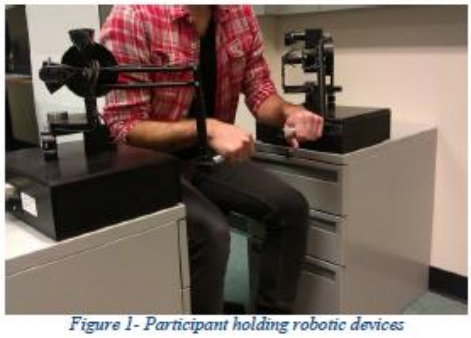

Figure 1- Participant holding robotic devices

Figure 2 - Setup

On a computer screen we will display a cursor and a target. You will have to move the cursor by moving your hands at the same time in the same direction. You will try to hit the targets on the screen at different elevations: shoulder, chest and knee height. You will reach towards 4 targets (one at a time) and come back to an initial position. You will repeat this process 20 times. If at any time you feel tired you will be able to take breaks between targets.

We will collect basic demographic data (age, gender, diagnosis) for this study. In addition, a physical therapist will perform a clinical assessment using the Fugl-Meyer Upper Extremity and the Modified Ashworth Scales, to measure your upper limb impairment and spasticity. During this assessment, he/she will require you to

move your upper limb in different directions and orientations. At the end of the session, a questionnaire will be provided to get your valuable feedback in terms of the ease of use and functionality of the system.

Who can Participate in this Study?

We are seeking adult stroke survivors who are willing to test the interactive system. They should be:

i. At least 19 years old.
ii. Weak one of side of their body (hemiplegic) as a result of a brain (cerebral) stroke.
iii. Only had one stroke
iv. The stroke was not caused by a hit to the head, accident, or fall.
v. Stroke occurred at least 6 months before this study
vi. Able to understand/follow directions and answer questions in English.
vii. Able to maintain a sitting position in a chair without arm rests, independently or with minimal supervision, for 1 hour
viii. Have the ability to perform the following movement several times with their weak arm (while seated): move their hand to their knee (on the same side as the weak arm), it's OK if they use their trunk to help themselves, and from that point of extension moving it up against gravity to chest height. They should be able to do this movement without any help from their strong hand.

Who Should not Participate in this Study?

Individuals that have:

i. Surgery in the arms, hands or trunk in the past 6 months
ii. Shoulder pain or instability (partial dislocation or subluxation)
iii. Trunk pain
iv. Other orthopedic or neurological conditions affecting the arm or trunk
v. Uncorrected visual impairment

How Many Participants Will Take Part in this Study?

We are aiming to recruit a total of 10 stroke survivors and 10 healthy adults to participate in this phase of the study.

Who is conducting the research?

The study is being conducted by Dr. Van der Loos and colleagues listed on the title page of this form.

What will this Study Cost Me?

This study will be no cost to you. All research-related medical care and treatment and any related tests that you will receive during your participation in this study will be provided at no cost to you.

What will you be asked to do?

You will be asked to read and sign this consent form. If you choose to consent, you will be considered a participant in the study. You will be asked to attend one session, conducted by Dr. Van der Loos or one of his colleagues, and assisted by a research assistant, and a physical therapist. It will be about 1.5 to 2 hours in duration. The study will be videotaped, a note taker will document important events as they occur, and the motion tracking data will be recorded. This is a requirement of the study. For more details about the confidentiality and use of the collected data, please refer to the Confidentiality and Anonymity section of this consent form.

Will there be any negative consequences for you by participating in this study?

Physical or mental fatigue could occur while using the system. If at any time you do not want to continue, you are under no obligation to do so. Dr. Van der Loos, the therapist, or one of the other researchers will also be available to answer your questions after the session.

What are the benefits to your participation in this study?

You may benefit from the knowledge that a new upper extremity therapy is being developed that could potentially be used by stroke survivors, and you may feel satisfied to know that you have contributed to the development of evidence-based practice in rehabilitation for stroke.

In addition, you will be compensated for your travel expenses based on transportation method and the distance between your home and the UBC campus. We will have this reimbursement ready for you when you come in for the study. However, if you prefer, you can bring your travel receipts when you come for the study, and we will send you a reimbursement for the exact amount in the mail afterwards. In addition to travel compensation, you will also receive a small thank you gift for participating.

After the Study is Finished

With your permission, you may be contacted in the future regarding your participation in other studies or phases of this project. At that time you can refuse to participate and your name will be removed from future correspondence.

If you would be interested in receiving more information about these future studies, please check the appropriate box at the end of this form.

If you are interested in the results of the study, you can contact the researchers and they will provide you with information about the results from this study.

Confidentiality and Anonymity

Dr. Van der Loos or one of his colleagues, a research assistant, and a physical therapist will be present in the room.

According to the UBC Policy on Scholarly Integrity, the notes, motion tracking data, and the videotaped recordings from the sessions will be used for the purposes of analysis and then destroyed after 5 years of the end of this study. All collected data will be kept in a secure, locked room at UBC for five years after the end of this study. We will blur identifying features in video and photographs presented in publications. Access to the photographs and video will be restricted to the investigators. We will use the collected data only in relation to this particular study. Information from these sessions will be used to design the software and hardware for the next phase of the project. Also, manuscripts based on the findings will be submitted to scientific journals for publication. In the event that quotes from a discussion are used, there will be no information included that could identify the speaker or the client, and you will not be identifiable in any report.

Your confidentiality will be respected. However, research records and health or other source records identifying you may be inspected in the presence of the investigator or his or her designated representatives on UBC Research Ethics Board for the purpose of monitoring the research. No information or records that disclose your identity will be published without your consent, nor will any information or records that disclose your identity be removed or released without your consent unless required by law.

You will be assigned a unique study number as a subject in this study. Only this number will be used on any research-related information collected about you during the course of this study, so that your identity [i.e. your name or any other information that could identify you] as a subject in this study will be kept confidential. Information that contains your identity will remain only with the Principal Investigator and/or designated representatives. The list that matches your name to the unique study number that is used on your research-related information will not be removed or released without your consent unless required by law.

Your rights to privacy are legally protected by federal and provincial laws that require safeguards to insure that your privacy is respected and also give you the right of access to the information about you that has been provided to the sponsor and, if need be, an opportunity to correct any errors in this information. Further details about these laws are available on request to the researchers.

What if you still have some questions?

If you have any questions or desire further information about this study before or during participation, you can contact Bulmaro Valdés, or the study principal investigator, Machiel (Mike) Van der Loos.

What Happens if Something Goes Wrong?

Signing this consent form in no way limits your or the subject's legal rights against the sponsor, investigators, or anyone else, and you do not release the researchers or participating institutions from their legal and professional responsibilities.

Do you have to participate?

Your participation is completely on a volunteer basis. There are no penalties if you do not wish to participate. There is no financial reward for participating. If you do volunteer, you have the right to withdraw at any time, for any reason, without penalty. Similarly, the researchers have the right to terminate this research project at any time.

If you do not wish to participate, you do not have to provide any reason for the decision nor will you lose the benefit of any medical care to which you are entitled or presently receiving.

Problems or Concerns

If you have any concerns or complaints about your rights as a research participant and/or your experiences while participating in this study, contact the Research Participant Complaint Line in the University of British Columbia Office of Research Ethics.

RIS:
Reaching in Stroke

Informed Consent Form: Stroke Survivors

My signature on this consent form means:

- I have read and understood the information in this consent form.
- I have had enough time to think about the information provided.
- I have been able to ask for advice if needed.
- I have been able to ask questions and have had satisfactory responses to my questions.
- I understand that all of the information collected will be kept confidential and that the results will only be used for scientific purposes.
- I understand that my participation in this study is voluntary.
- I understand that I am completely free at any time to refuse to participate or to withdraw from this study at any time, and that this will not change the quality of care that I receive.
- I understand that I am not waiving any of my legal rights as a result of signing this consent form.
- I understand that there is no guarantee that this study will provide any benefits to me.
- For participants unable to sign for themselves: The consent form was read to the participant, and the person signing below attests that the study was accurately explained to, and apparently understood by, the participant (please check if participant is unable to read) **[ ]**
- I will receive a signed copy of this consent form for my own records.

Participant Signature: _____

Participant Name: _____

Date: _____

In addition and separately, I agree to allow my comments to be quoted in reports or publications. If a quote were used, there would be nothing in the quote that could identify me.

Participant Signature: _____

Participant Name: _____

Date: _____

OPTIONAL INFORMATION:

i) Yes, please contact me:
[ ] with information about participating in future studies
Phone/email:

_____

_____	_____	_____
Printed Name, Principal Investigator	Signature, Principal Investigator	Date

A.2 Chapter 3 Consent Form

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Mechanical Engineering

Informed Consent Form: Stroke Survivors

RIS:
Reaching in Stroke Phase 2

Principal Investigator
Name: Hendrik F. Machiel (Mike) Van der Loos
Position title: Associate Professor
Organization: UBC Department of Mechanical Engineering

Co-Applicants
Name: Bulmaro A. Valdés Benavides
Position title: PhD Candidate
Organization: UBC Biomedical Engineering Program

Contact Person:
Please contact Bulmaro Valdés or Hendrik F. Machiel (Mike) Van der Loos, in the event of any unusual occurrences or difficulties related to this research.

Funding Agency
The Peter Wall Solutions Initiative (PWSI) of the Peter Wall Endowment at UBC is funding this study. Information on this funding initiative can be found at: http://research.ubc.ca/vpri/ubc-peter-wall-solutions-initiative

Introduction

We invite you to take part in a research study being conducted by Mike Van der Loos, who is a professor at the University of British Columbia, and his colleagues. Your participation in this study is voluntary and you may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study will likely not benefit you directly, but we might learn things that will benefit others. You should discuss any questions you have about this study with Dr. Van der Loos or the other investigators present.

Your Participation is voluntary

Your participation is voluntary. You have the right to refuse to participate in this study. If you decide to participate, you may still choose to withdraw from the study at any time without any negative consequences to the medical care, education, or other services to which you are entitled or are presently receiving.

You should be aware that there is a difference for both you and your doctor between being a patient and being a research participant. As a patient all medical procedures and treatments are carried out for your benefit only according to standard accepted practice. As a research participant you and your doctor also must take into account the requirements for the research study. These may include procedures and treatments that are not part of standard practice or are not yet proven. This consent form describes the diagnostic and treatment procedures that are being carried out for research purposes. Please review the consent document carefully when deciding whether or not you wish to be part of the research and sign this consent only if you accept being a research participant.

If you wish to participate in this study, you will be asked to sign this form.
Please take time to read the following information carefully and to discuss it with your family, friends, and doctor before you decide.

Purpose of the Study

The purpose of this study is to investigate how bimanual reaching movements of stroke survivors are affected when we provide participants with either visual or force cues. We propose to use a motion tracking camera (Microsoft Kinect) and two robotic devices (Jaco Kinova) to obtain information about the way the users' hands and bodies move in space when they reach forward with both hands.

We will use the results from this study to develop systems that will focus on the quality of the movements of stroke survivors when they rehabilitate at home using commercially available technology.

Study Design

In this study, we will ask you to perform a set of forward reaching movements while holding two robotic devices in your hands (Figure 1). If you cannot hold the devices, we can use velcro straps to hold them in your hands. At the same time a motion tracking camera will be analyzing the movement of your body while you perform the reaching activities (Figure 2). During the session, you will be seated in an office chair without armrests.

Figure 1- Participant holding robotic devices

Figure 2 - Setup

On a computer screen we will display two cursor and a target. You will have to move the cursors by moving your hands at the same time in the same direction. You will try to hit the target on the screen by extending your arms at knee height. You will reach towards one target and come back to an initial position.

Based on how well you are performing the movements we will give you either visual (change of color fill of the two computer cursors) or force (change on how much the robots resist your movement) feedback, so that you can be aware that your movements need to be corrected. You will perform 120 reaches with feedback, plus another 60 in which you will not receive any feedback. You will be able to rest after every 15 targets, and between feedback conditions. In addition, if at any time you feel tired you will be able to take breaks between targets.

We will collect basic demographic data (age, gender, diagnosis) for this study. In addition, a physical therapist will perform a clinical assessment using the Fugl-Meyer Upper Extremity and the Reaching Performance Scale, to measure your upper limb impairment and spasticity. During this assessment, he/she will require you to move your upper limb in different directions and orientations. At the end of the session, a questionnaire will be provided to get your valuable feedback in terms of the ease of use and functionality of the system.

Who can Participate in this Study?

We are seeking adult stroke survivors who are willing to test the interactive system. They should be:

i. At least 19 years old.
ii. Weak one of side of their body (hemiplegic) as a result of a brain (cerebral) stroke.
iii. The stroke was not caused by a hit to the head, accident, or fall.
iv. Stroke occurred at least 3 months before this study
v. Able to understand/follow directions and answer questions in English.
vi. Able to maintain a sitting position in a chair without arm rests, independently or with minimal supervision, for 1.5 hours
vii. Have the ability to perform the following movement several times with their weak arm (while seated): move their hand to their hip (on the same side as the weak arm), it's OK if they use their trunk to help themselves, and from that point of flexion moving it forward (without touching their thigh) to touch their knee (on the same side as the weak arm). They should be able to do this movement without any help from their strong hand.

Who Should not Participate in this Study?

Individuals that have:

i. Surgery in the arms, hands or trunk in the past 3 months
ii. Shoulder pain or instability (partial dislocation or subluxation)
iii. Trunk pain
iv. Other orthopedic or neurological conditions affecting the arm or trunk
v. Severe uncorrected visual impairment that could prevent participants from completing the task

How Many Participants Will Take Part in this Study?

We are aiming to recruit a total of 20 stroke survivors to participate in this phase of the study.

Who is conducting the research?

The study is being conducted by Dr. Van der Loos and colleagues listed on the title page of this form.

What will this Study Cost Me?
This study will be no cost to you. All research-related medical care and treatment and any related tests that you will receive during your participation in this study will be provided at no cost to you.

What will you be asked to do?

You will be asked to read and sign this consent form. If you choose to consent, you will be considered a participant in the study. You will be asked to attend one session, conducted by Dr. Van der Loos or one of his colleagues, and assisted by a research assistant, and a physical therapist. It will be about 2.0 to 2.5 hours in duration. Only the Reaching Performance Scale assessment will be videotaped, so the therapist can score your movements after the study is completed. A note taker will document important events as they occur, and the motion tracking data will be recorded. This is a requirement of the study. For more details about the confidentiality and use of the collected data, please refer to the Confidentiality and Anonymity section of this consent form.

Will there be any negative consequences for you by participating in this study?

Physical or mental fatigue could occur while using the system. If at any time you do not want to continue, you are under no obligation to do so. Dr. Van der Loos, the therapist, or one of the other researchers will also be available to answer your questions after the session.

What are the benefits to your participation in this study?

You may benefit from the knowledge that a new upper extremity therapy is being developed that could potentially be used by stroke survivors, and you may feel satisfied to know that you have contributed to the development of evidence-based practice in rehabilitation for stroke.

In addition, you will be compensated for your travel expenses based on transportation method and the distance between your home and the UBC campus. We will have this reimbursement ready for you when you come in for the study. However, if you prefer, you can bring your travel receipts when you come for the study, and we will send you a reimbursement for the exact amount in the mail afterwards. In addition to travel compensation, you will also receive $26 CAD as compensation for your time.

After the Study is Finished

With your permission, you may be contacted in the future regarding your participation in other studies or phases of this project. At that time you can refuse to participate and your name will be removed from future correspondence.

If you would be interested in receiving more information about these future studies, please check the appropriate box at the end of this form.

If you are interested in the results of the study, you can contact the researchers and they will provide you with information about the results from this study.

Confidentiality and Anonymity

Dr. Van der Loos or one of his colleagues, a research assistant, and a physical therapist will be present in the room.

According to the UBC Policy on Scholarly Integrity, the notes, motion tracking data, and the videotaped recordings from the sessions will be used for the purposes of analysis and then destroyed after 5 years of the end of this study. All collected data will be kept in a secure, locked room at UBC for five years after the end of this study. We will blur identifying features in video and photographs presented in publications. Access to the photographs and video will be restricted to the investigators. We will use the collected data only in relation to this particular study. Information from these sessions will be used to design the software and hardware for the next phase of the project. Also, manuscripts based on the findings will be submitted to scientific journals for publication. In the event that quotes from a discussion are used, there will be no information included that could identify the speaker or the client, and you will not be identifiable in any report.

Your confidentiality will be respected. However, research records and health or other source records identifying you may be inspected in the presence of the investigator or his or her designated representatives on UBC Research Ethics Board for the purpose of monitoring the research. No information or records that disclose your identity will be published without your consent, nor will any information or records that disclose your identity be removed or released without your consent unless required by law.

You will be assigned a unique study number as a subject in this study. Only this number will be used on any research-related information collected about you during the course of this study, so that your identity [i.e. your name or any other information that could identify you] as a subject in this study will be kept confidential. Information that contains your identity will remain only with the Principal Investigator and/or designated representatives. The list that matches your name to the unique study number that is used on your research-related information will not be removed or released without your consent unless required by law.

Your rights to privacy are legally protected by federal and provincial laws that require safeguards to insure that your privacy is respected and also give you the right of access to the information about you that has been provided to the sponsor and, if need be, an opportunity to correct any errors in this information. Further details about these laws are available on request to the researchers.

What if you still have some questions?

If you have any questions or desire further information about this study before or during participation, you can contact Bulmaro Valdés, or the study principal investigator, Machiel (Mike) Van der Loos.

What Happens if Something Goes Wrong?

Signing this consent form in no way limits your or the subject's legal rights against the sponsor, investigators, or anyone else, and you do not release the researchers or participating institutions from their legal and professional responsibilities.

Do you have to participate?

Your participation is completely on a volunteer basis. There are no penalties if you do not wish to participate. If you do volunteer, you have the right to withdraw at any time, for any reason, without penalty. Similarly, the researchers have the right to terminate this research project at any time.

If you do not wish to participate, you do not have to provide any reason for the decision nor will you lose the benefit of any medical care to which you are entitled or presently receiving.

Problems or Concerns

If you have any concerns or complaints about your rights as a research participant and/or your experiences while participating in this study, contact the Research Participant Complaint Line in the University of British Columbia Office of Research Ethics.

RIS:
Reaching in Stroke

Informed Consent Form: Stroke Survivors

My signature on this consent form means:

- I have read and understood the information in this consent form.
- I have had enough time to think about the information provided.
- I have been able to ask for advice if needed.
- I have been able to ask questions and have had satisfactory responses to my questions.
- I understand that all of the information collected will be kept confidential and that the results will only be used for scientific purposes.
- I understand that my participation in this study is voluntary.
- I understand that I am completely free at any time to refuse to participate or to withdraw from this study at any time, and that this will not change the quality of care that I receive.
- I understand that I am not waiving any of my legal rights as a result of signing this consent form.
- I understand that there is no guarantee that this study will provide any benefits to me.
- For participants unable to sign for themselves: The consent form was read to the participant, and the person signing below attests that the study was accurately explained to, and apparently understood by, the participant (please check if participant is unable to read) **[ ]**
- I will receive a signed copy of this consent form for my own records.

Participant Signature: _____

Participant Name: _____

Date: _____

In addition and separately, I agree to allow my comments to be quoted in reports or publications. If a quote were used, there would be nothing in the quote that could identify me.

Participant Signature: _____

Participant Name: _____

Date: _____

OPTIONAL INFORMATION:

i) Yes, please contact me:
[ ] with information about participating in future studies
Phone/email:

_____

_____	_____	_____
Printed Name, Principal Investigator	Signature, Principal Investigator	Date

A.3 Chapter 4 Consent Form

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Mechanical Engineering

Informed Consent Form: Stroke Survivors

RIS:
Reaching in Stroke Phase 3

Principal Investigator
Name: Hendrik F. Machiel (Mike) Van der Loos
Position title: Associate Professor
Organization: UBC Department of Mechanical Engineering

Co-Applicants
Name: Bulmaro A. Valdés Benavides
Position title: PhD Candidate
Organization: UBC Biomedical Engineering Program

Contact Person:
Please contact Bulmaro Valdés or Hendrik F. Machiel (Mike) Van der Loos, in the event of any unusual occurrences or difficulties related to this research.

Funding Agency
The Natural Sciences and Engineering Research Council of Canada through the Discovery Grants Program (http://www.nserc-crsng.gc.ca/Professors-Professeurs/Grants-Subs/DGIGP-PSIGP_eng.asp), the Networks of Centres of Excellence through the NeuroDevNet Initiative (http://www.neurodevnet.ca/), and the University of British Columbia Faculty of Graduate and Post Doctoral Studies through the Public Scholars Initiative (https://www.grad.ubc.ca/psi) are funding this study.

Introduction

We invite you to take part in a research study being conducted by Mike Van der Loos, who is a professor at the University of British Columbia, and his colleagues. Your participation in this study is voluntary and you may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study will likely not benefit you directly, but we might learn things that will benefit others. You should discuss any questions you have about this study with Dr. Van der Loos or the other investigators present.

Your Participation is voluntary

Your participation is voluntary. You have the right to refuse to participate in this study. If you decide to participate, you may still choose to withdraw from the study at any time without any negative consequences to the medical care, education, or other services to which you are entitled or are presently receiving.

You should be aware that there is a difference for both you and your doctor between being a patient and being a research participant. As a patient all medical procedures and treatments are carried out for your benefit only according to standard accepted practice. As a research participant you and your doctor also must take into account the requirements for the research study. These may include procedures and treatments that are not part of standard practice or are not yet proven. This consent form describes the diagnostic and treatment procedures that are being carried out for research purposes. Please review the consent document carefully when deciding whether or not you wish to be part of the research and sign this consent only if you accept being a research participant.

If you wish to participate in this study, you will be asked to sign this form.
Please take time to read the following information carefully and to discuss it with your family, friends, and doctor before you decide.

Purpose of the Study

The purpose of this study is to investigate how bimanual reaching movements of stroke survivors are affected when we provide participants with visual+force cues, and game scores. We propose to use a motion tracking camera (Microsoft Kinect) and two robotic devices (Jaco Kinova) to obtain information about the way the users' hands and bodies move in space when they reach forward with both hands.

We will use the results from this study to develop systems that will focus on the quality of the movements of stroke survivors when they rehabilitate at home using commercially available technology.

Study Design

In this study, we will ask you to perform a set of forward reaching movements while holding two robotic devices in your hands (Figure 1). If you cannot hold the devices, we can use velcro straps to hold them in your hands. At the same time a motion tracking camera will be analyzing the movement of your body while you perform the reaching activities (Figure 2). During the session, you will be seated in an office chair without armrests.

Figure 1- Participant holding robotic devices

Computer Screen

Robotic Devices

Figure 2 - Setup

Motion Tracking Camera

On a computer screen we will display two cursor and a target. You will have to move the cursors by moving your hands at the same time in the same direction. You will try to hit the target on the screen by extending your arms at knee height. You will reach towards one target and come back to an initial position.

Based on how well you are performing the movements we will give you visual (change of color fill of the two computer cursors), force (change on how much the robots resist your movement) feedback, or points (game scores), so that you can be aware that your movements need to be corrected. You will perform 120 reaches with feedback, plus another 60 in which you will not receive any feedback. You will be able to rest after every 15 targets, and between feedback conditions. In addition, if at any time you feel tired you will be able to take breaks between targets.

We will collect basic demographic data (age, gender, diagnosis) for this study. In addition, a physical therapist will perform a clinical assessment using the Fugl-Meyer Upper Extremity and the Reaching Performance Scale, to measure your upper limb impairment and spasticity. During this assessment, he/she will require you to move your upper limb in different directions and orientations. At the end of the session, a questionnaire will be provided to get your valuable feedback in terms of the ease of use and functionality of the system.

Who can Participate in this Study?

We are seeking adult stroke survivors who are willing to test the interactive system. They should be:

i. At least 19 years old.
ii. Weak one of side of their body (hemiplegic) as a result of a brain (cerebral) stroke.
iii. The stroke was not caused by a hit to the head, accident, or fall.
iv. Stroke occurred at least 3 months before this study
v. Able to understand/follow directions and answer questions in English.
vi. Able to maintain a sitting position in a chair without arm rests, independently or with minimal supervision, for 1.5 hours
vii. Have the ability to perform the following movement several times with their weak arm (while seated): move their hand to their hip (on the same side as the weak arm), it's OK if they use their trunk to help themselves, and from that point of flexion moving it forward (without touching their thigh) to touch their knee (on the same side as the weak arm). They should be able to do this movement without any help from their strong hand.

Who Should not Participate in this Study?

Individuals that have:

i. Surgery in the arms, hands or trunk in the past 3 months
ii. Shoulder pain or instability (partial dislocation or subluxation)
iii. Trunk pain
iv. Other orthopedic or neurological conditions affecting the arm or trunk
v. Severe uncorrected visual impairment that could prevent participants from completing the task

How Many Participants Will Take Part in this Study?

We are aiming to recruit a total of 20 stroke survivors to participate in this phase of the study.

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After the Study is Finished

With your permission, you may be contacted in the future regarding your participation in other studies or phases of this project. At that time you can refuse to participate and your name will be removed from future correspondence.

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RIS:
Reaching in Stroke

Informed Consent Form: Stroke Survivors

My signature on this consent form means:

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- I have been able to ask for advice if needed.
- I have been able to ask questions and have had satisfactory responses to my questions.
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- I understand that my participation in this study is voluntary.
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- I will receive a signed copy of this consent form for my own records.

Participant Signature: _____

Participant Name: _____

Date: _____

In addition and separately, I agree to allow my comments to be quoted in reports or publications. If a quote were used, there would be nothing in the quote that could identify me.

Participant Signature: _____

Participant Name: _____

Date: _____

OPTIONAL INFORMATION:

i) Yes, please contact me:
[ ] with information about participating in future studies
Phone/email:

_____

_____	_____	_____
Printed Name, Principal Investigator	Signature, Principal Investigator	Date

Appendix B Clinical Scales

This appendix presents information about the clinical scales administered to participants during the different phases of this project.

B.1 Modified Ashworth Scale

The Modified Ashworth Scale measures abnormal muscle tone through resistance to passive movements [33]. The scale employs six rating levels (0, 1, 1+, 2, 3, and 4) to evaluate muscle tone, with a score of 0 indicating no increase in muscle tone, and a maximum score of 4 indicating rigidity in flexion or extension. Full instructions and the scale are available online[5]. The intra- and inter-rater reliability of the scale have been found to be good to very good for the wrist, elbow, and knee [93].

B.2 Fugl-Meyer Upper Extremity Scale

The Fugl-Meyer Upper Extremity Scale measures upper extremity impairment in people post-stoke [82]. The scale has 33 items that are scored using three different rating levels (0, 1, and 2), with a score of 0 indicating that the movement cannot be performed, and a maximum score of 2 indicating that the movement can be fully performed. Full instructions and the scale are available online[6]. The scale has been shown to have good intra- an inter-rater reliability [94].

[5] http://www.rehabmeasures.org/PDF%20Library/Modified%20Ashworth%20Scale%20Instructions.pdf
[6] http://www.gu.se/digitalAssets/1328/1328946_fma-ue-english.pdf

B.3 Reaching Performance Scale

The Reaching Performance Scale was developed to measure compensatory movements of the upper extremities of hemiparetic stroke survivors during reaching to grasp tasks [65]. In this scale, the level of motor compensation is quantified by asking participants to reach and grasp an object placed within and beyond their arms' reach. The scale evaluates the movements in 6 different components: trunk displacement, movement smoothness, shoulder movement, elbow movement, prehension, and a global score. Each component is scored using four rating levels (0, 1, 2, and 3), with 0 indicating a maximum level of compensation or an inability to complete the task, and a score of 3 indicating an adequate movement. Full instructions and the scale are available online[7]. Preliminary intra- and inter-rater reliability of the whole scale have been found to be acceptable [65].

[7] https://academic.oup.com/ptj/article/84/1/8/2805317/Development-and-Validation-of-a-Scale-for-Rating#55132303

Appendix C Chapter 3 Post-Test Questionnaire

This appendix presents the post-test questionnaire and results from Chapter 3. The questionnaire was administered at the end of the intervention.

C.1 Post-Test Questionnaire

Date:_____ **Participant Number:** _____

RIS (Reaching in Stroke)

Phase 2 Post-Test Questionnaire: Stroke Survivors

1. **Sex (circle one):** Male Female
2. **Age:** _____
3. **Height:** _____
4. **Dominant hand before stroke (circle one):** Left Right
5. **Weaker side of my body (circle one):** Left Right
6. **Site of Stroke:** _____
7. **Type of Stroke (please circle):** Hemorrhagic Ischemic
8. **Time since stroke:** _____
9. **Therapy services I receive:**_____
10. **How often do you receive therapy?** _____

Date:_____ **Participant Number:** _____

We would like your feedback on your experience trying the RIS system.

For the following statements, please circle the answer that best represents how strongly you feel about each statement.

A. Reaching Task:

1. **It was easy to control the cursor with my strong hand:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **It was easy to control the cursor with my weak hand:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **I felt tired after completing the session:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

4. **It was difficult to reach the targets:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ **Participant Number:** _____

5. **To be able to reach the targets, I had to move my trunk:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

B. Visual Feedback (i.e., the gradual change in the color of the cursor from ---- to red when you used your trunk):

1. **It was difficult to understand the visual feedback**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **It was difficult to see the visual feedback**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **When I received visual feedback I reduced how much I was moving my trunk**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

C. Force Feedback (i.e., robots resisted movement when you used your trunk):

1. **It was difficult to understand the force feedback**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **It was difficult to feel the force feedback**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **When I received force feedback I reduced how much I was moving my trunk**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

D. Feedback Comparison:

1. **To reduce my trunk movements I would prefer to receive:**

Visual feedback	Force feedback	Both	None	Other

Why?

_____

_____

_____

In addition, if you answered "other" please tell us what you meant by "other":

_____

_____

Date:_____ Participant Number: _____

E. System Design:

1. **The robotic devices limited my reaching movements:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **I felt comfortable grasping the robotic devices:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **The robotic devices felt heavy in my hands:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

4. **I felt unsafe using the robotic devices:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

5. **I would use these robotic devices for rehabilitation:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ **Participant Number:** _____

6. **It was hard for me to see the targets and cursor on the computer's monitor:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

7. **I felt comfortable maintaining a proper seated posture:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ **Participant Number:** _____

F. System Usability Scale (SUS): © Digital Equipment Corporation, 1986.

In the following statements, "**system**" refers to the target game and the robotic devices. Please circle the number that best represents how strongly you feel about each statement.

1. I think that I would like to use this system frequently:

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. I found the system unnecessarily complex:

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. I thought the system was easy to use:

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

4. I think that I would need the support of a technical person to be able to use this system:

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

5. **I found the various functions in this system were well integrated:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

6. **I thought there was too much inconsistency in this system:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

7. **I would imagine that most people would learn to use this system very quickly:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

8. **I found the system very cumbersome to use:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

9. **I felt very confident using the system:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

10. I needed to learn a lot of things before I could get going with this system:

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

G. System's Features:

1. **Please complete the following sentence: "My favorite features of this system were..."**

_____

_____

_____

2. **Please complete the following sentence: "My least favorite features of this system were..."**

_____

_____

_____

3. **Is there anything that you would change about the system?**

_____

_____

_____

Thank you for your participation!

C.2 Post-Test Questionnaire Results

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

REDUCING TRUNK COMPENSATION IN STROKE SURVIVORS: A RANDOMIZED CROSSOVER TRIAL COMPARING VISUAL VS. FORCE FEEDBACK MODALITIES

POST-TEST QUESTIONNAIRE RESULTS

BULMARO VALDÉS, ANDREA SCHNEIDER, MIKE VAN DER LOOS

RREACH Lab
Robotics for Rehabilitation Exercise and Assessment in Collaborative Healthcare

POST-TEST QUESTIONNAIRE PART A (REACHING TASK) A.1-A.4

Part A of the Post- Test Questionnaire:

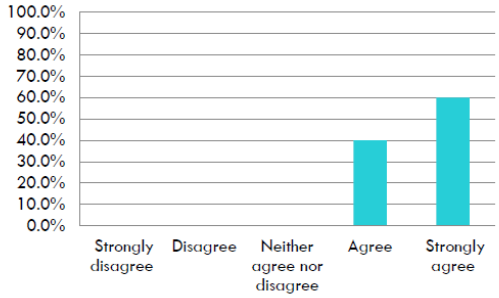
- Likert Scale comprised of 4 Likert-type questions (A.1-A.4)
- Examined the underlying belief that: "The level of difficulty of the reaching task was adequate for stroke survivors"

	Part A
Average	3.73
SD	0.8

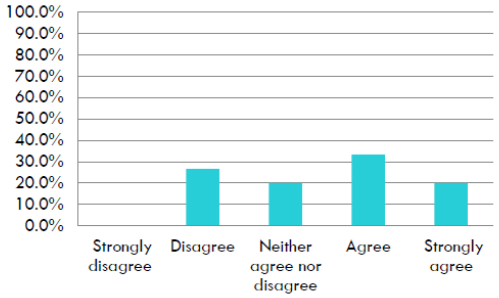
On average people agreed that the level of difficulty of the reaching task was adequate for stroke survivors
T-test against neutral response, *t*(14)=3.53, *p*=0.003, *d*= *0.91*, *95%CI* (3.29, 4.18)**

POST-TEST QUESTIONNAIRE PART A (REACHING TASK) A.1-A.4

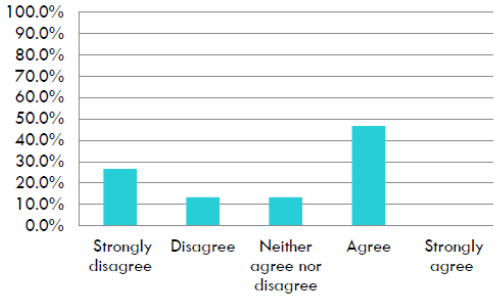
A.1 It was easy to control the cursor with my strong hand



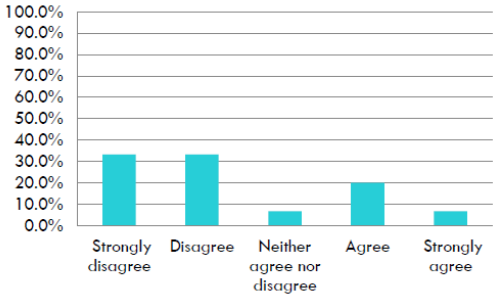
A.2 It was easy to control the cursor with my weak hand



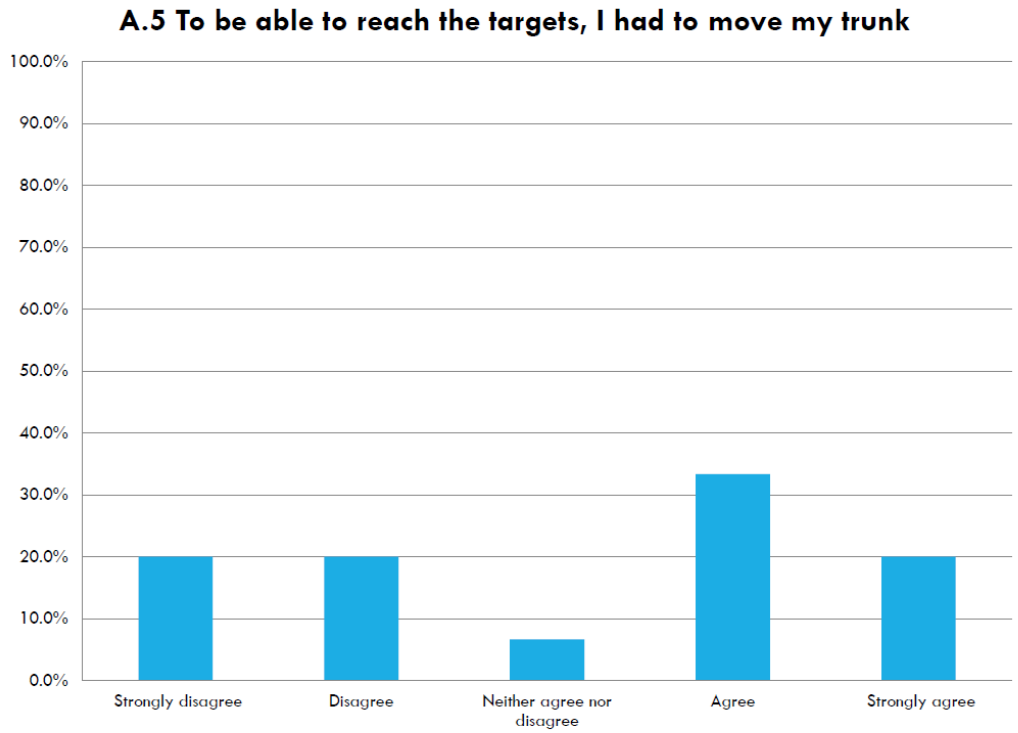
A.3 I felt tired after completing the session



A.4 It was difficult to reach the targets



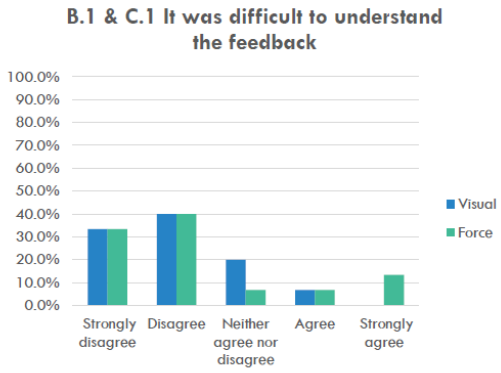
POST-TEST QUESTIONNAIRE PART A (REACHING TASK) A.5



Combined categories:

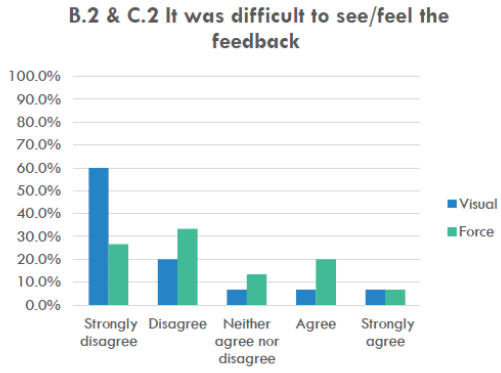
- 53.3% Agree
- 6.7% Neutral
- 40% Disagree

POST-TEST QUESTIONNAIRE PART B & C (FEEDBACK)



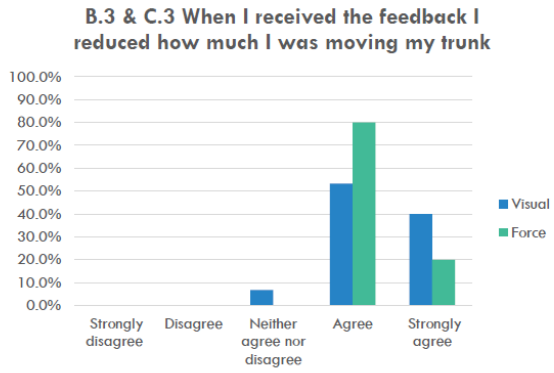
Mode		
Visual	2	Disagree
Force	2	Disagree

Feedbacks not difficult to understand



Mode		
Visual	1	Strongly Disagree
Force	2	Disagree

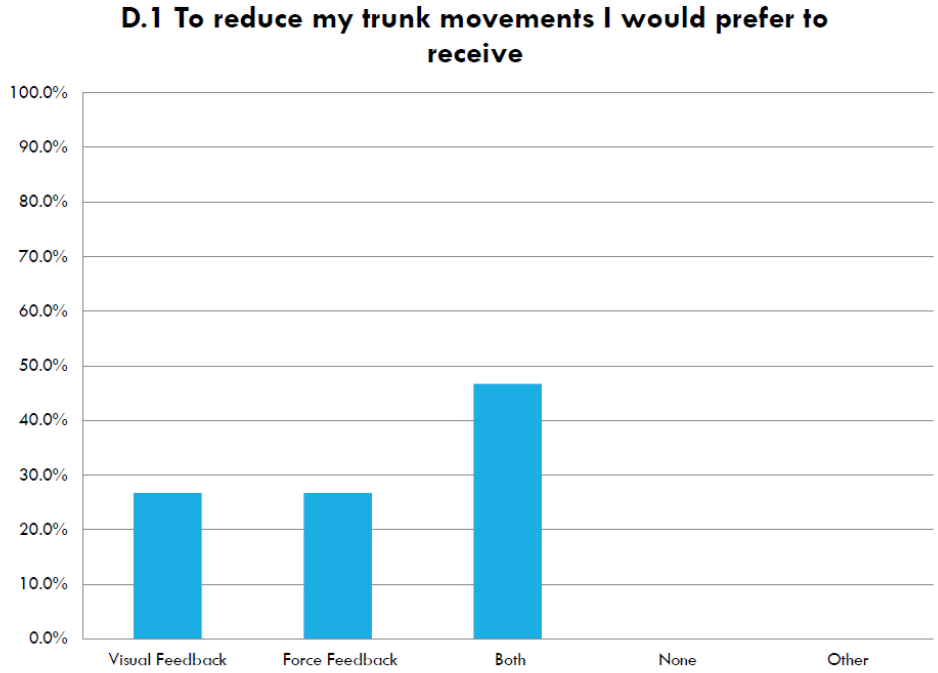
Feedbacks not difficult to perceive



Mode		
Visual	4	Agree
Force	4	Agree

Feedbacks reduced trunk compensation

POST-TEST QUESTIONNAIRE PART D (FEEDBACK COMPARISON)



POST-TEST QUESTIONNAIRE PART D (FEEDBACK COMPARISON) D.1 COMMENTS

For the ones that answered "Visual":

- *"If I can see it, its easier to control"*
- *"To have a chance to think more about the trunk compensation"*
- *"It's like a strong feeling to do the correct exercise when I see the visual feedback I don't want to fill up the red colour"*
- *"Both visual feedback right arm"*

For the ones that answered "Force":

- *"Added resistance with force feedback"*
- *"Better reminder to not use my trunk"*
- *"Simple to understand"*

For the ones that answered "Both":

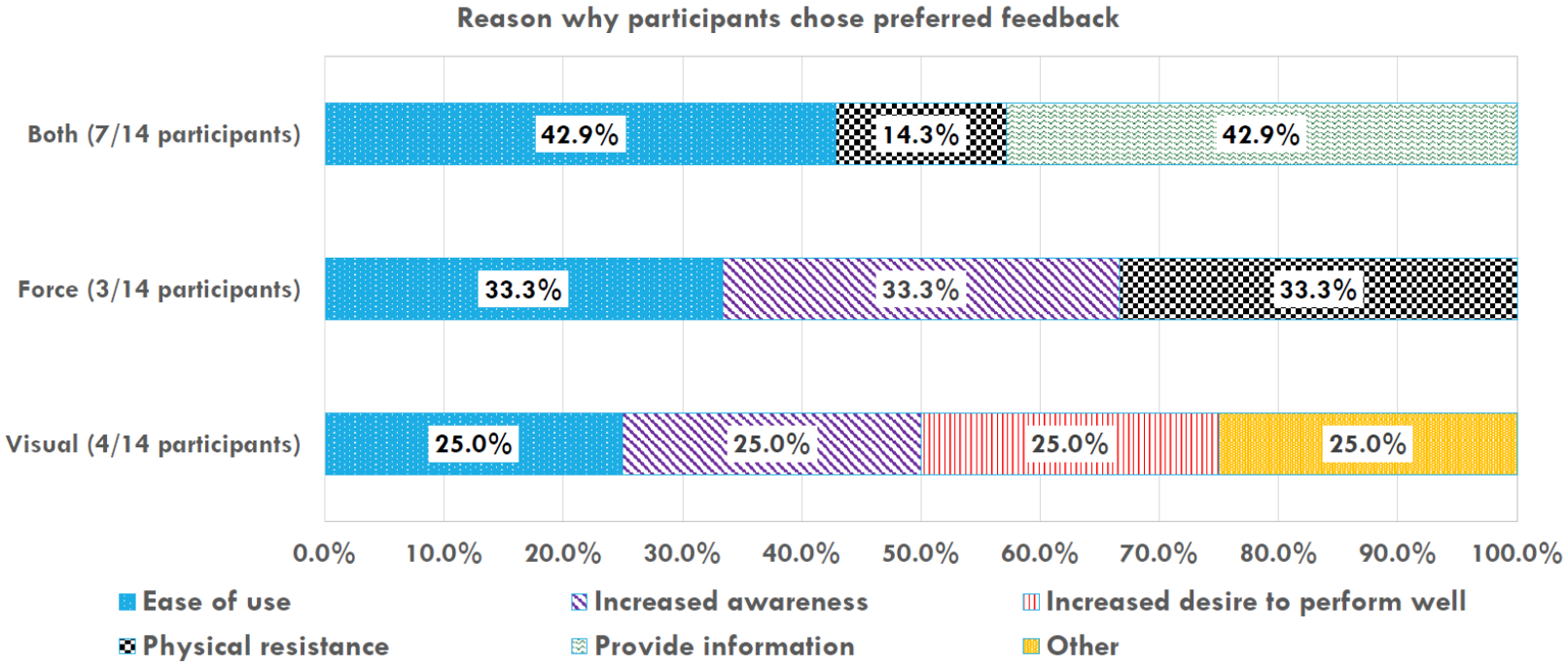
- *"Because both give me guidance in my hand and trunk movement"*
- *"Its easier to have both"*
- *"Because they both seem to work"*
- *"More information"*
- *"Visual feedback is good but it relies heavily on my noticing the feedback on the screen. Forced feedback can't be ignored"*
- *"Easy to get better feedback from both rather than just one"*
- *"I understand both equally"*

POST-TEST QUESTIONNAIRE PART D (FEEDBACK COMPARISON) D.1 COMMENTS, CONTENT ANALYSIS

For participants (14/15) who answered why they chose a specific type of feedback to reduce their trunk compensation, the main reasons they gave were:

- **Ease of use:** The feedback was easy to understand, perceive, and worked well.
- **Increased awareness**: The feedback increased the participants' awareness of their trunk compensation levels.
- **Increased desire to perform well:** The feedback motivated participants to perform better by reducing their trunk compensation.
- **Physical resistance:** Participants liked receiving the added resistance provided by the robotic devices.
- **Provide information:** The feedback provided movement information to participants.

POST-TEST QUESTIONNAIRE PART D (FEEDBACK COMPARISON) D.1 COMMENTS, CONTENT ANALYSIS



POST-TEST QUESTIONNAIRE PART E (SYSTEM DESIGN) E.1-E.7

Part E of the Post- Test Questionnaire:

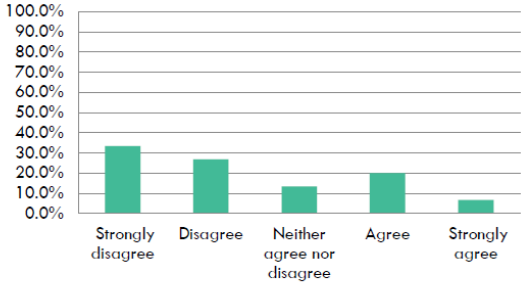
- Likert Scale comprised of 7 Likert-type questions (E.1-E.7)
- Examined the underlying belief that: "the system's design is appropriate for performing reaching movements for rehabilitation"

	Part E
Average	4.19
SD	0.51

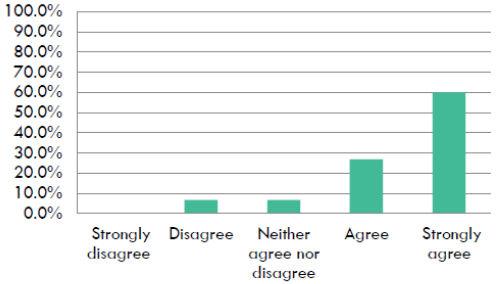
On average people agreed that system was appropriate for performing reaching movements for rehabilitation.
T-test against neutral response, $t(14)=9.07$, $p=0.000$*, $d=2.34$, $95\%CI$ (3.909, 4.472)**

POST-TEST QUESTIONNAIRE PART E (SYSTEM DESIGN) E.1-E.3

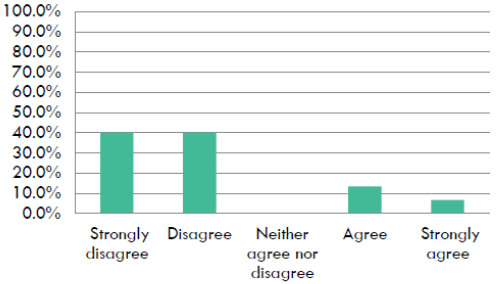
E.1 The robotic devices limited my reaching movements



E.2 I felt comfortable grasping the robotic devices

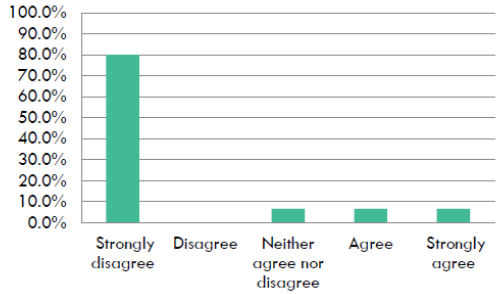


E.3 The robotic devices felt heavy in my hands

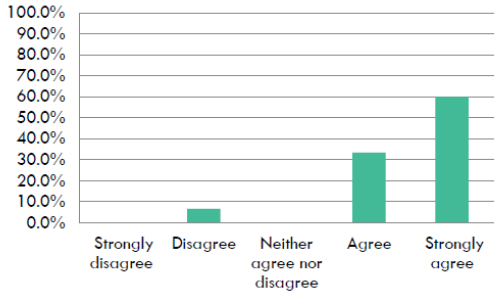


POST-TEST QUESTIONNAIRE PART E (SYSTEM DESIGN) E.4-E.7

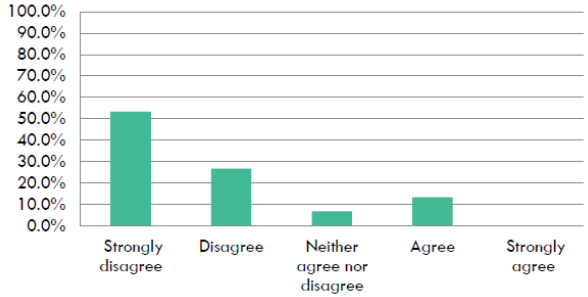
E.4 I felt unsafe using the robotic devices



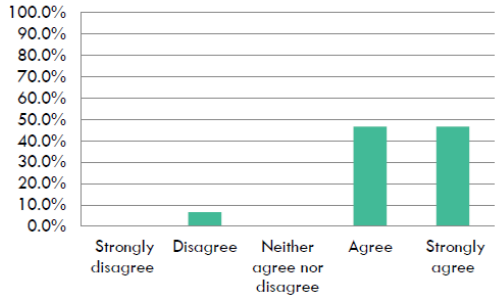
E.5 I would use these robotic devices for rehabilitation



E.6 It was hard for me to see the targets and cursor on the computer's monitor



E.7 I felt comfortable maintaining a proper seated posture



POST-TEST QUESTIONNAIRE PART F (SUS) F.1-F.10

System Usability Scale (SUS): "A reliable, low-cost usability scale that can be used for global assessments of systems usability."[1]

- It consists of a 10 item questionnaire with five response options for respondents
- **A value above 68 is considered above average. Although the scores are 0-100, these are not percentages.**
- Adjective ratings are[2]: "Worst Imaginable", "Awful", "Poor", "OK", "Good", "Excellent", and "Best Imaginable".

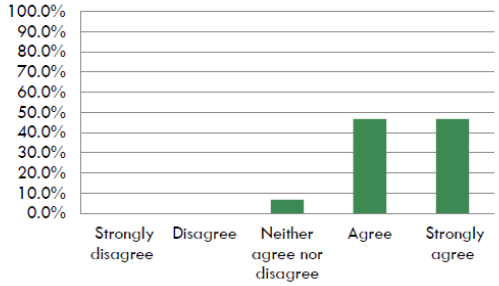
	SUS Score
Average	76
SD	13

On average system can be considered "Good"

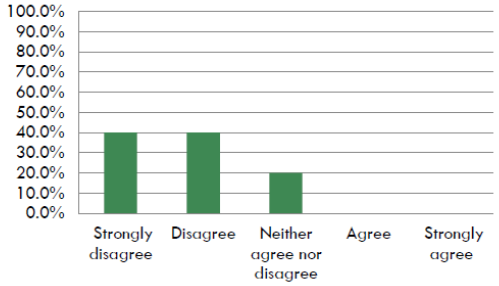
[1] Brooke J. SUS-A quick and dirty usability scale. In: Usability evaluation in industry. 1996. p. 4–7.
[2] Bangor A, Kortum P, Miller J. Determining what individual SUS scores mean: Adding an adjective rating scale. Journal of usability studies. 2009;4(3):114–123.

POST-TEST QUESTIONNAIRE PART F (SUS) F.1-F.10

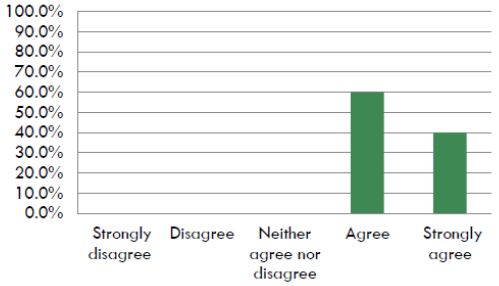
F.1 I think that I would like to use this system frequently



F.2 I found the system unnecessarily complex

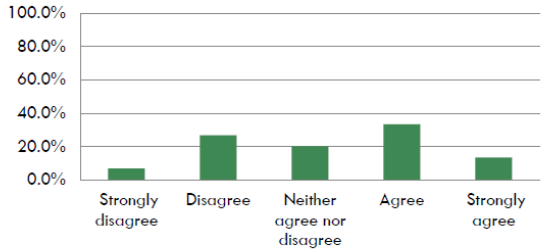


F.3 I thought the system was easy to use

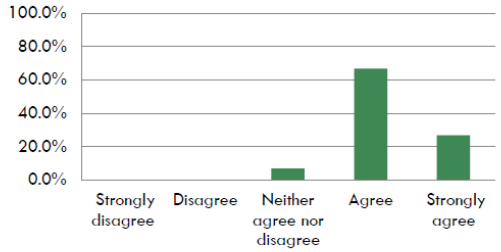


POST-TEST QUESTIONNAIRE PART F (SUS) F.1-F.10

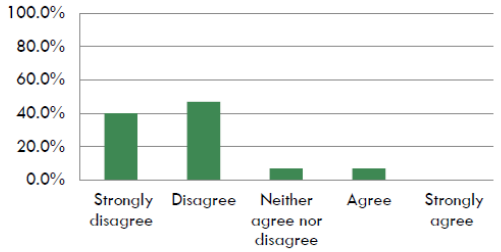
F.4 I think that I would need the support of a technical person to be able to use this system



F.5 I found the various function in this system were well integrated

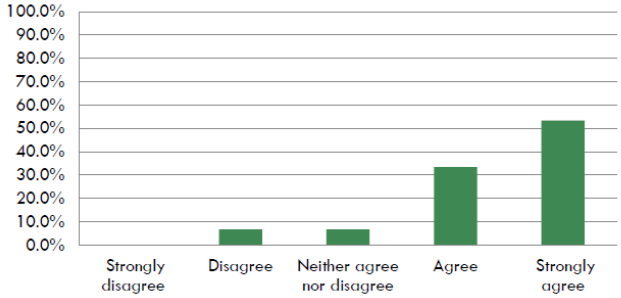


F.6 I thought there was too much inconsistency in this system

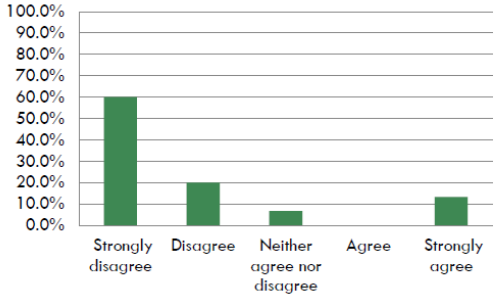


POST-TEST QUESTIONNAIRE PART F (SUS) F.1-F.10

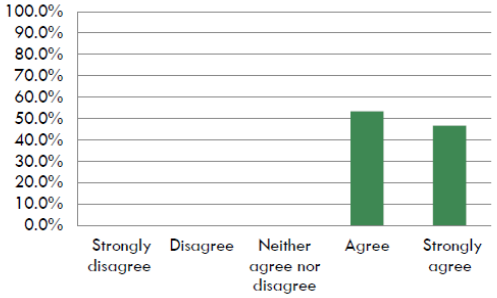
F.7 I would imagine that most people would learn to use this system very quickly



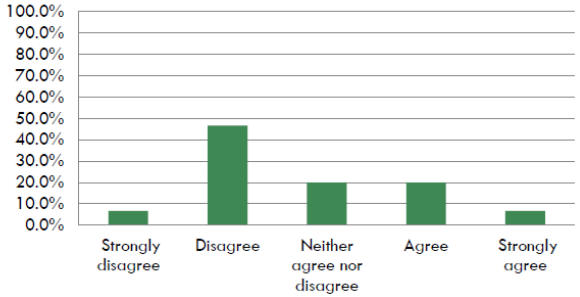
F.8 I found the system very cumbersome to use



F.9 I felt very confident using the system



F.10 I needed to learn a lot of things before I could get going with this system



POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.1-G.3

G.1 My favourite features:

- "Easy to use, the challenge was getting my movements to learn"
- "Liked to move affected arm"
- "Liked all aspects of system, it was good"
- "Easy to understand, well organized"
- "Feels like game rehab, it was fun. It was exercise and game, rehab combination"
- "Liked them all"
- "Learned not to use my trunk when moving, I have to think of reducing moving my trunk"
- "The system was a fun and reasonable for a disabled person"
- "That is was simple to use and the staff were helpful"
- "The robotic arm"
- "Its entertaining as well as therapeutic"
- "Arms"
- "Liked the whole system and I liked video games"
- "Ease of understanding"
- "The red little bit, good (liked the visual feedback)"

G.2 My least favorite features:

- None
- None
- None
- None
- None
- None
- "Hand movements"
- "When I use the visual feedback"
- "Hurt thumb on left hand (stroke arm)"
- "My weak arm being tied to the robotic arm"
- None
- None
- None
- None
- None

G.3 Anything that you would change:

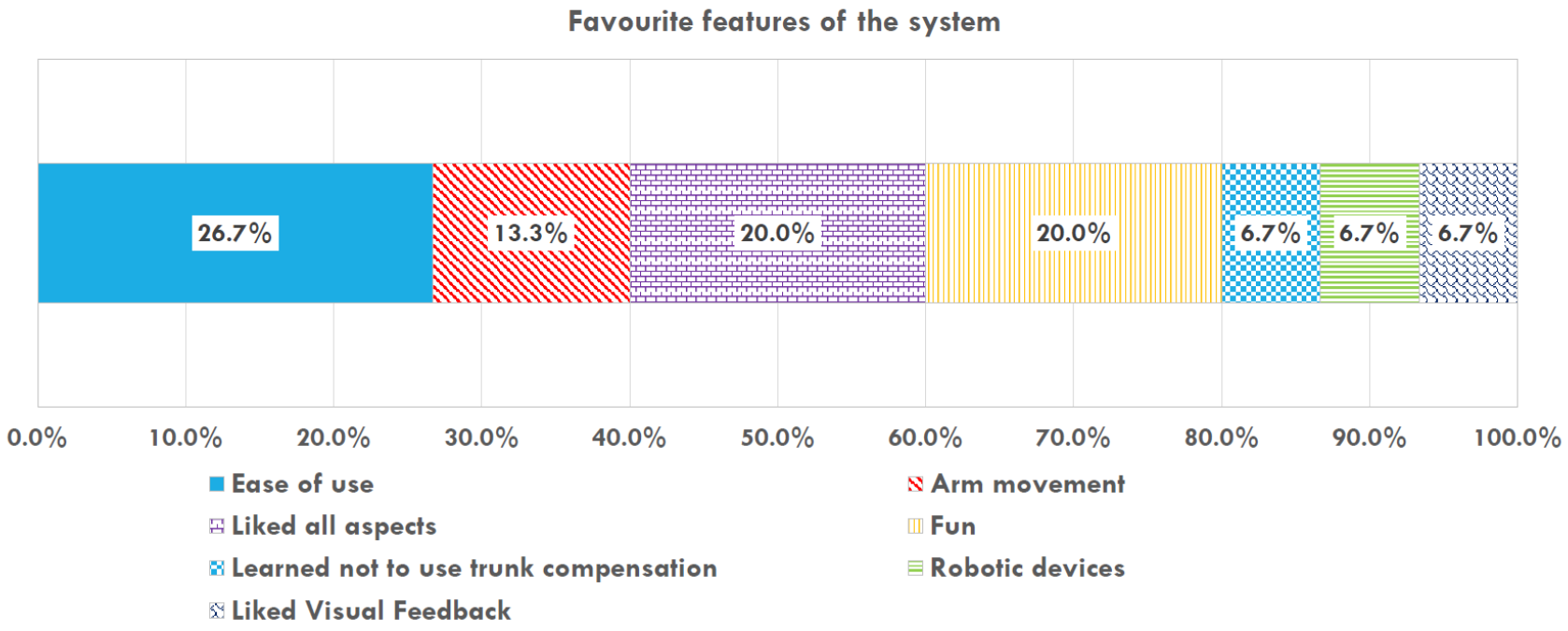
- "None"
- "None"
- "No, confusing at first screen shows up/down motions but asking for forward/back motion"
- "None"
- "None"
- "None"
- "None"
- "Nothing and I hope to contribute to the disability community with a special tool to improve the quality of life"
- "None"
- "None"
- "Use the same feedback system to make more game type scenarios. It is good the way it is but over time could become tedious."
- "None"
- "None"
- "None"
- "Little better 'Red'"

POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.1,CONTENT ANALYSIS

For participants (15/15) who answered about their favourite features of the system, their main answers were:

- **Ease of use:** The system was simple and easy to use and understand.
- **Arm movement:** Participants liked that the system required them to move their arms.
- **Liked all aspects:** Participants liked all features of the system.
- **Fun:** The system was fun to use and felt like a game.
- **Learned not to use trunk compensation:** Participants learned not to use trunk compensatory movements.
- **Robotic devices:** Participants liked using the system's robotic devices.
- **Liked Visual Feedback:** Participants liked receiving visual feedback about their trunk compensation.

POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.1,CONTENT ANALYSIS

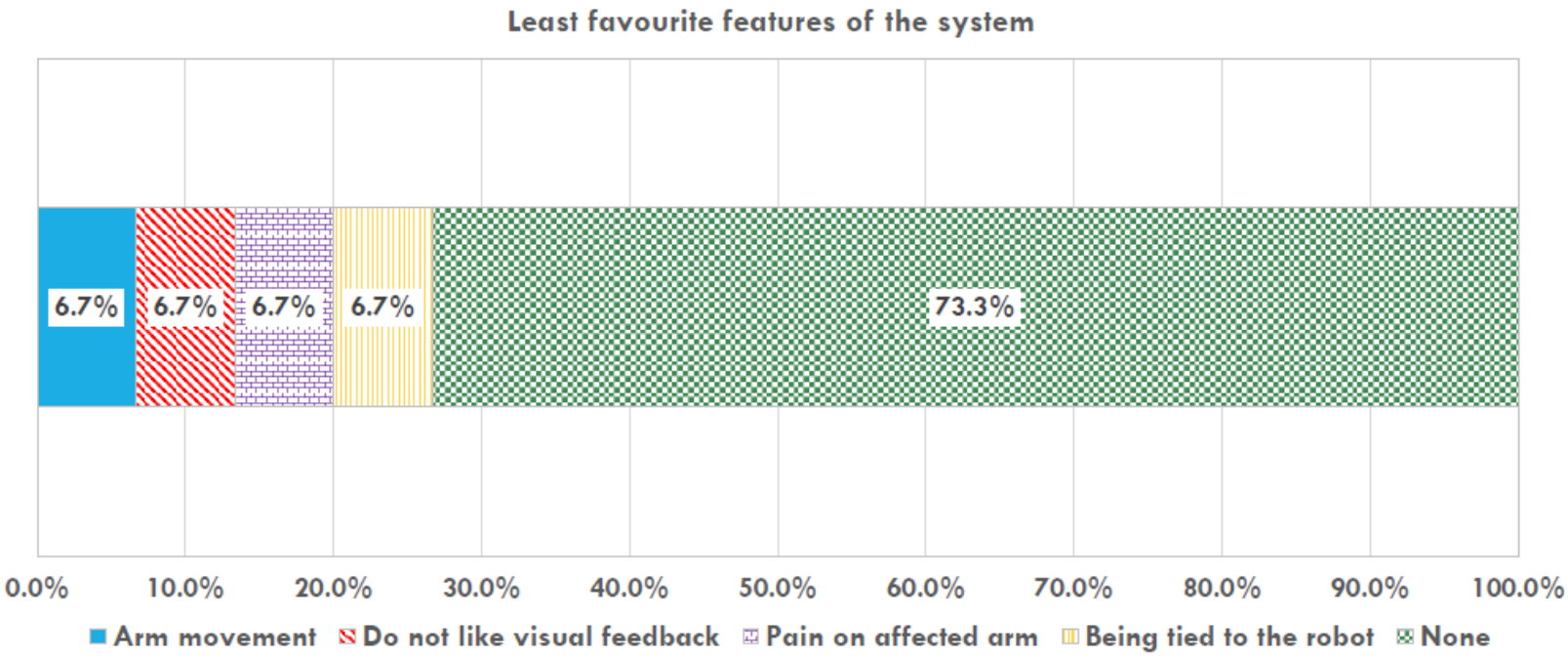


POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.2,CONTENT ANALYSIS

For participants (15/15) who answered about their least favourite features of the system, their main answers were:

- **Arm movement:** Participants did not like that the system required them to move their arms.
- **Do not like Visual Feedback:** Participants did not like receiving Visual Feedback about their trunk compensation.
- **Pain on affected arm:** Participants felt pain after completing the study.
- **Being tied to the robot:** Participants did not like to have their hand strapped to the robot.
- **None:** Participants liked all features of the system.

POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.2,CONTENT ANALYSIS

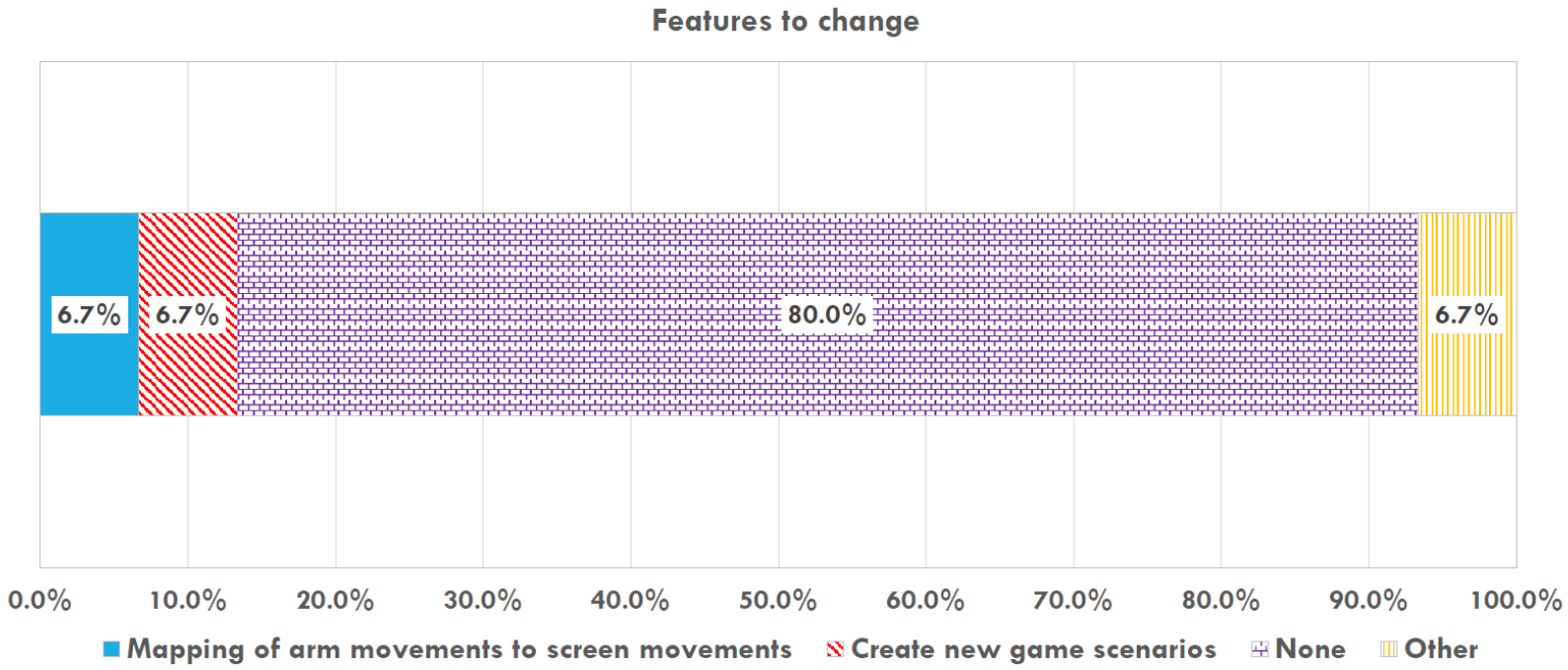


POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.3,CONTENT ANALYSIS

For participants (15/15) who answered if there was anything that they would change about the system, their main answers were:

- **Mapping of arm movements to screen movements:** Participants found confusing that they had to move their arms forward to make the cursors go up in the screen.
- **Create new game scenarios:** Participants would like to have more game scenarios as current task could become tedious over time.
- **None:** Participants did not want to change anything about the system.

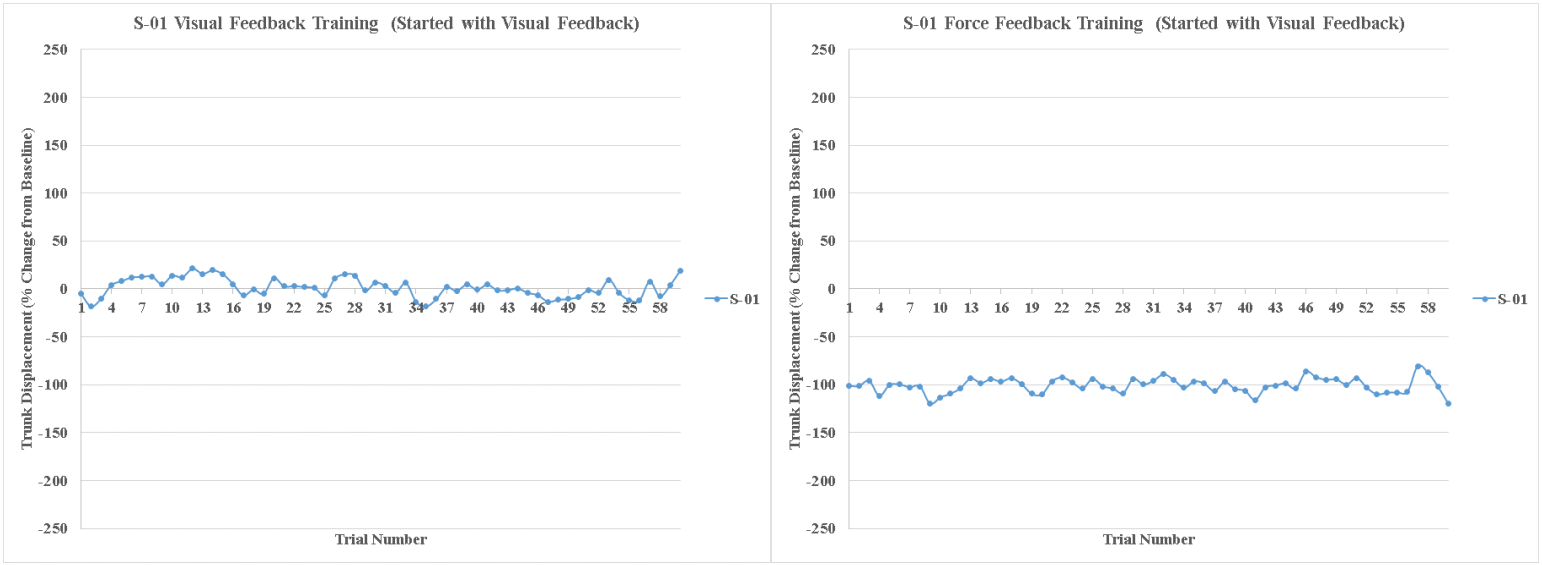
POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.3,CONTENT ANALYSIS

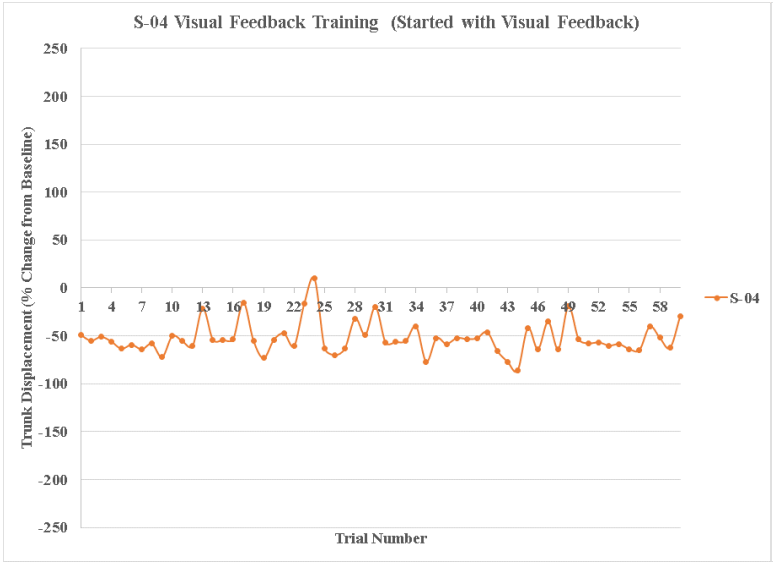


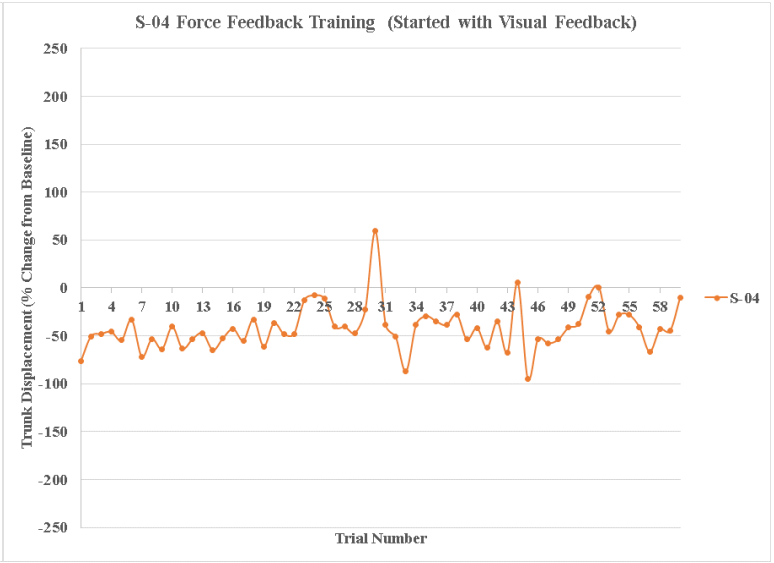
Appendix D Chapter 3 Participants' Trunk Displacement Data During Training Trials

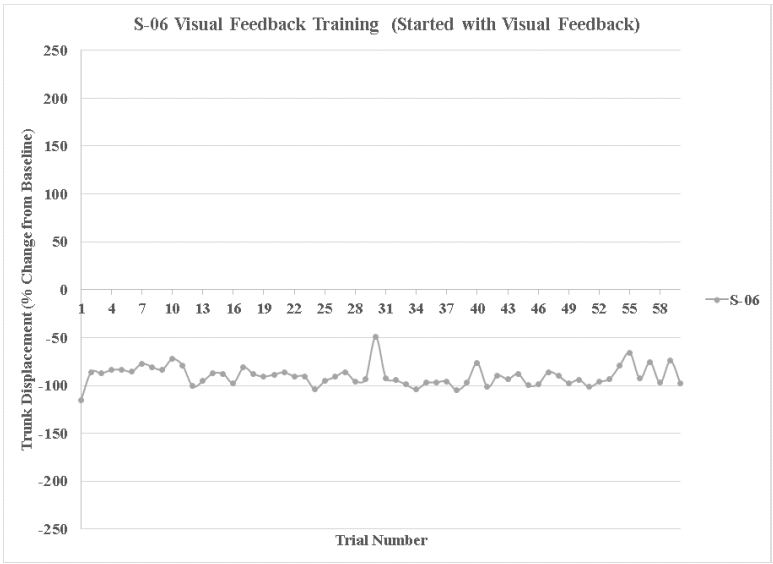
This appendix presents the individual trunk displacement data during the training trials when feedback was active.

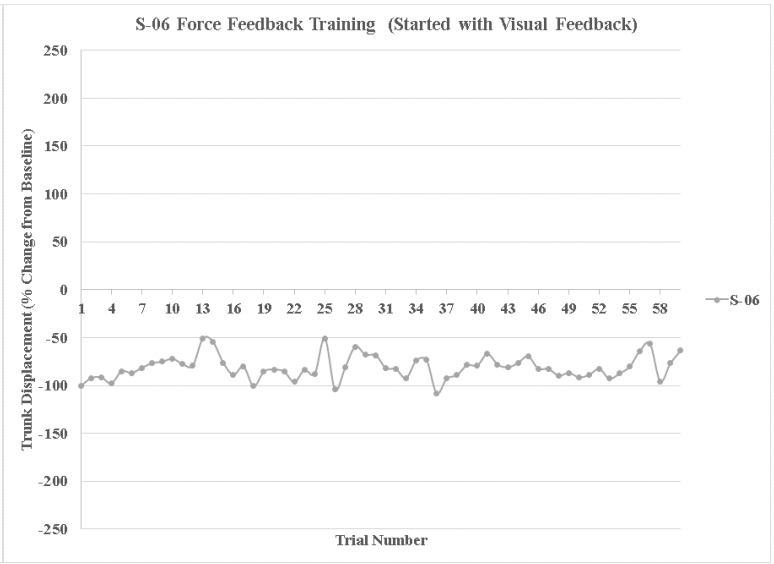
D.1 Participants who Started with Visual Feedback

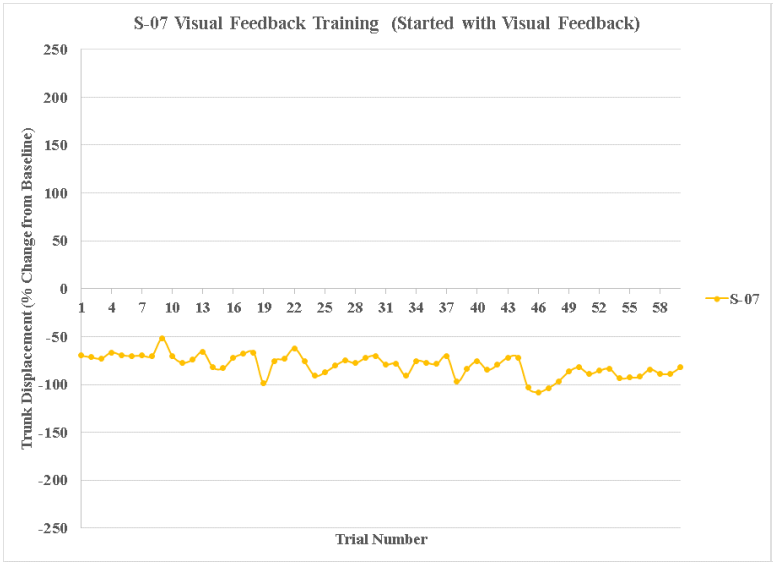


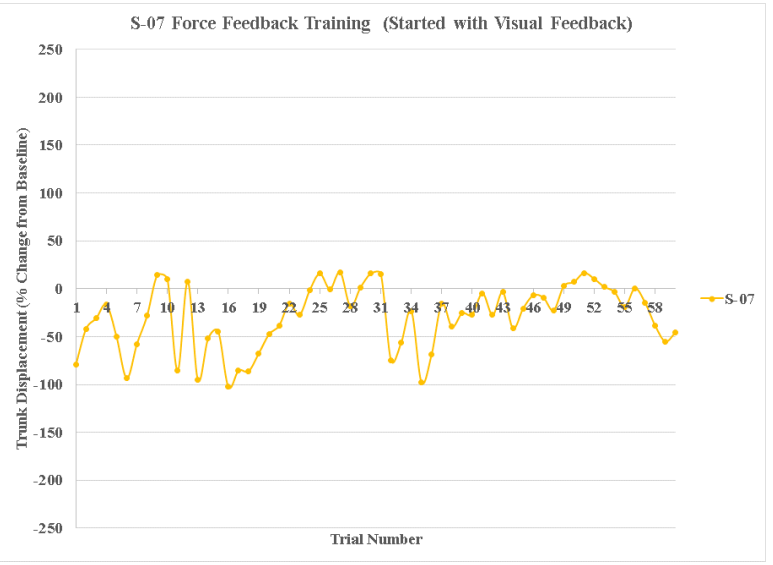

S-04 Visual Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-04

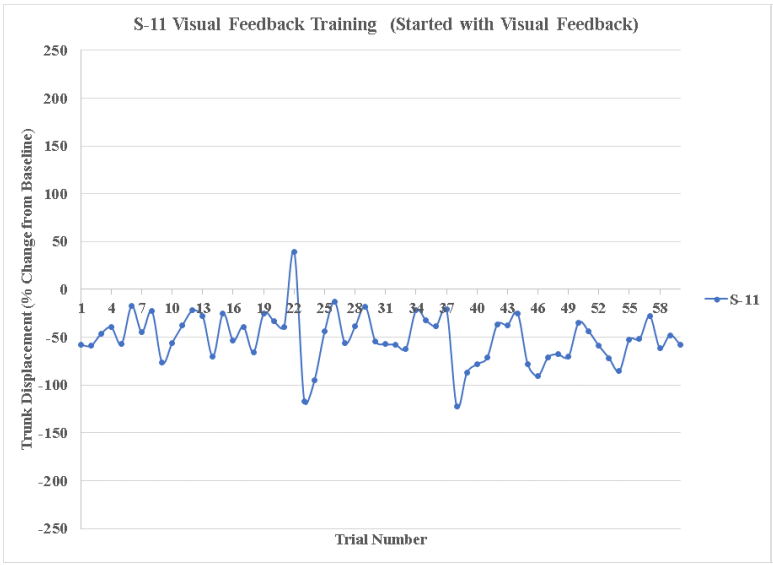

S-04 Force Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-04

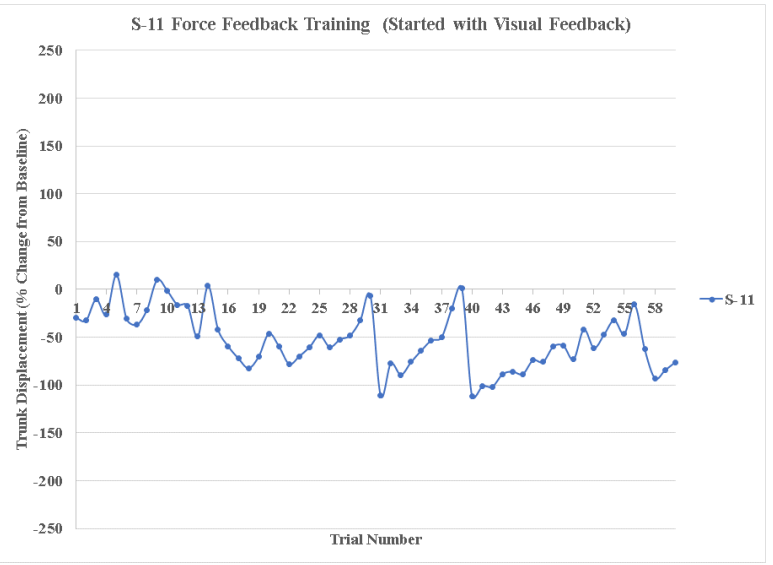

S-06 Visual Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-06

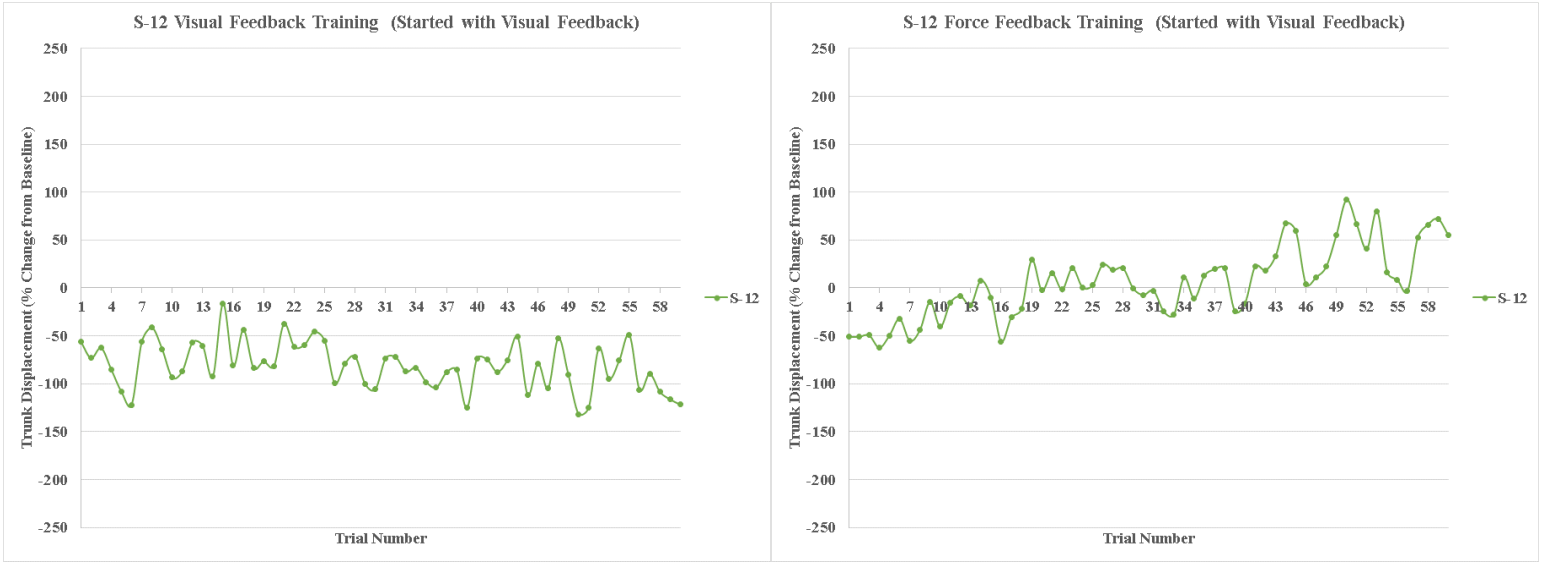

S-06 Force Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-06

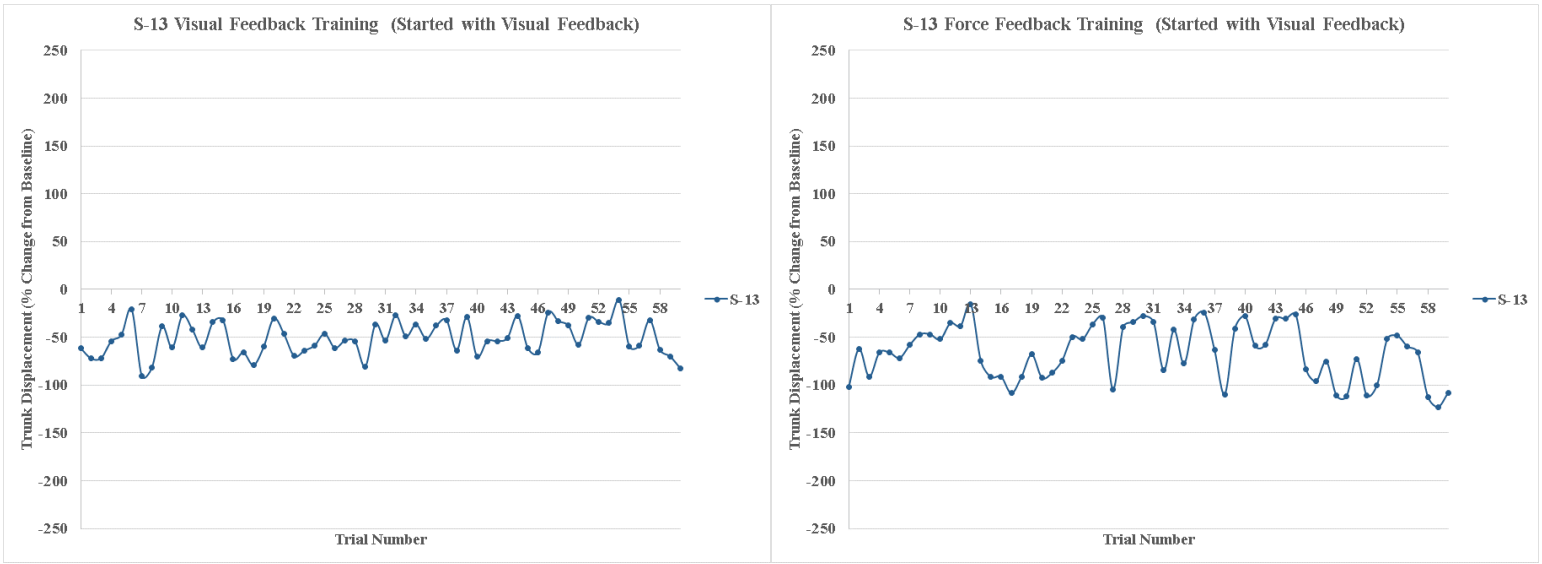

S-07 Visual Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-07

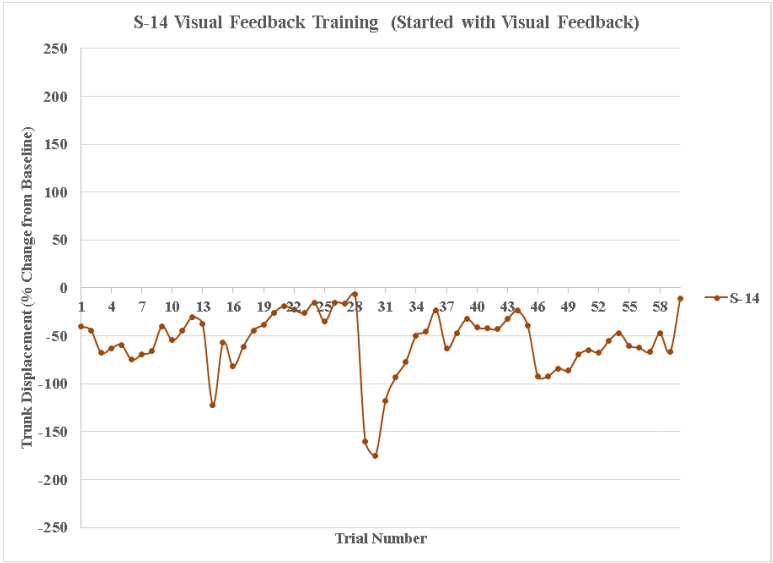

S-07 Force Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-07

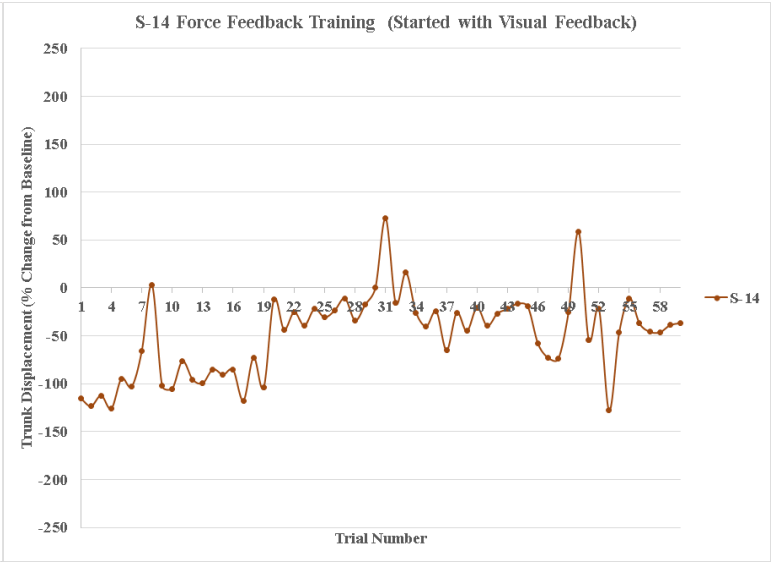

S-11 Visual Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-11


S-11 Force Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-11

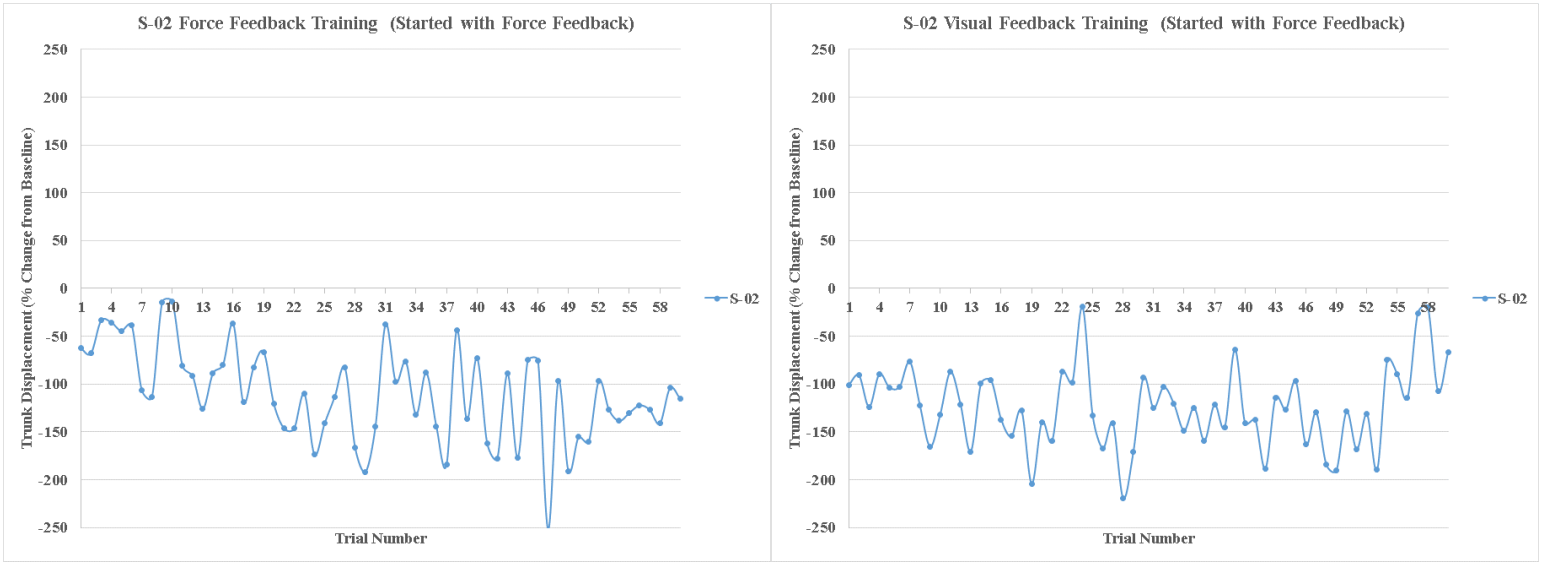

S-12 Visual Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-12
S-12 Force Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-12

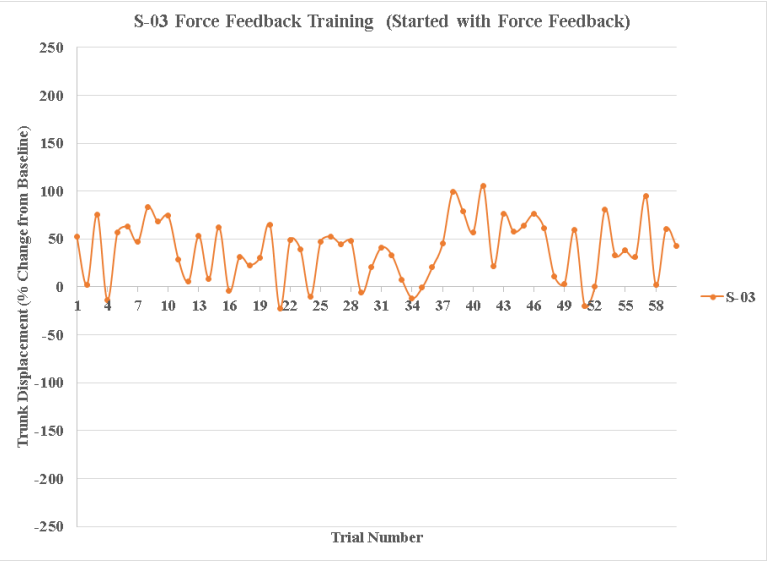

S-13 Visual Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-13
S-13 Force Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-13

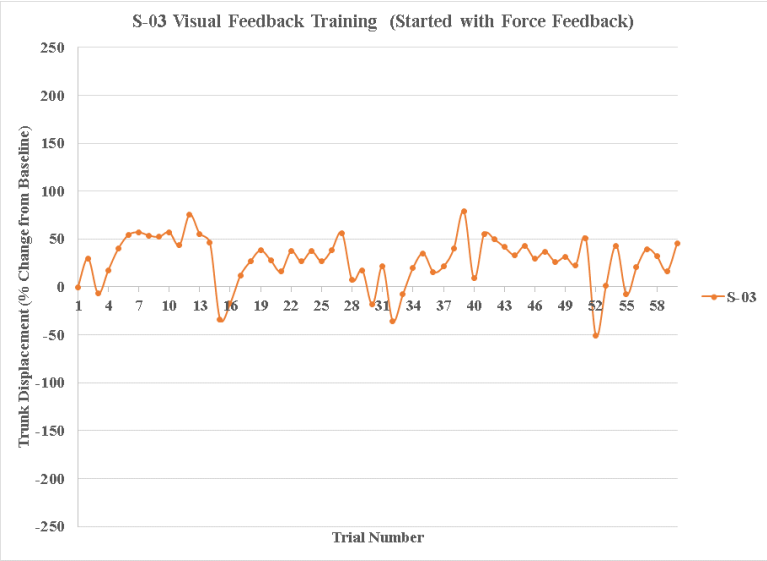

S-14 Visual Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-14

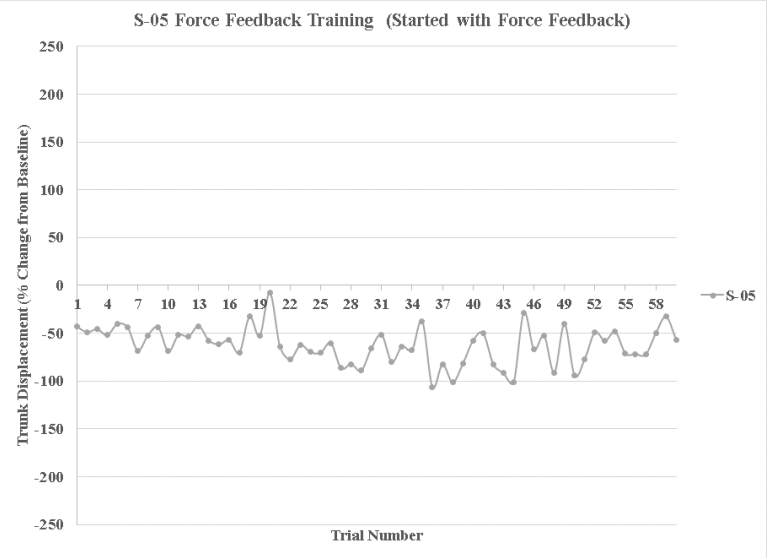

S-14 Force Feedback Training (Started with Visual Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-14

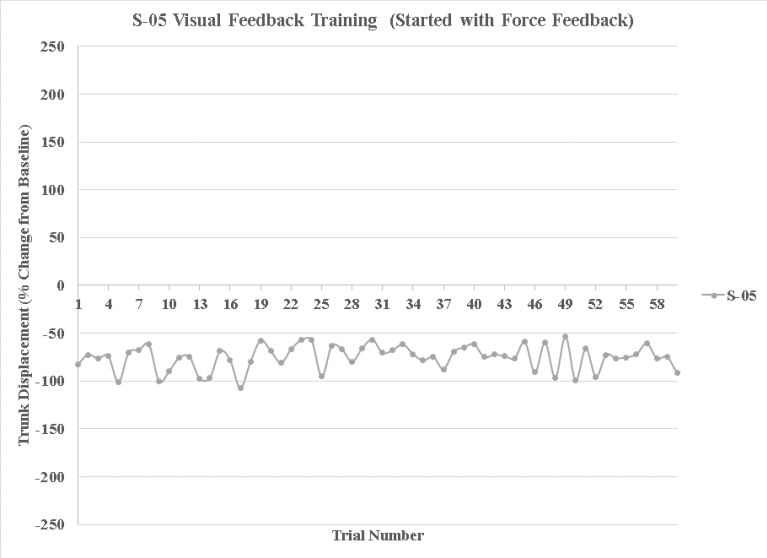
D.2 Participants who Started with Force Feedback

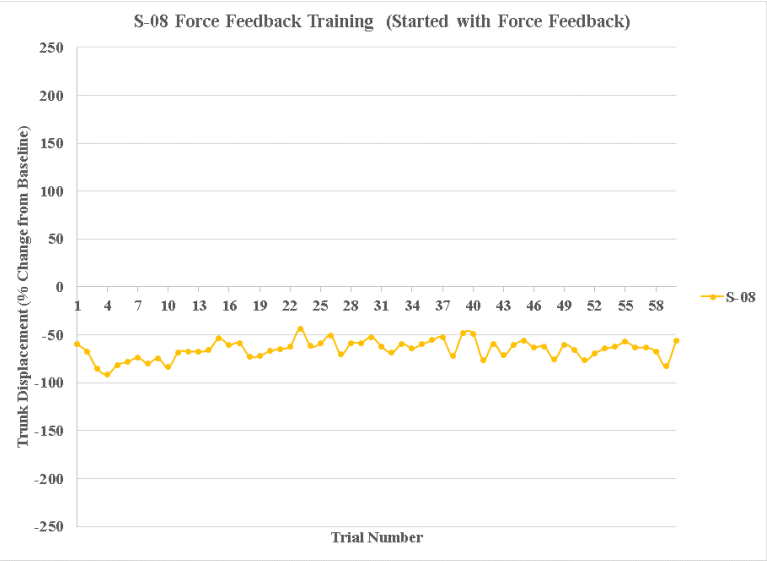


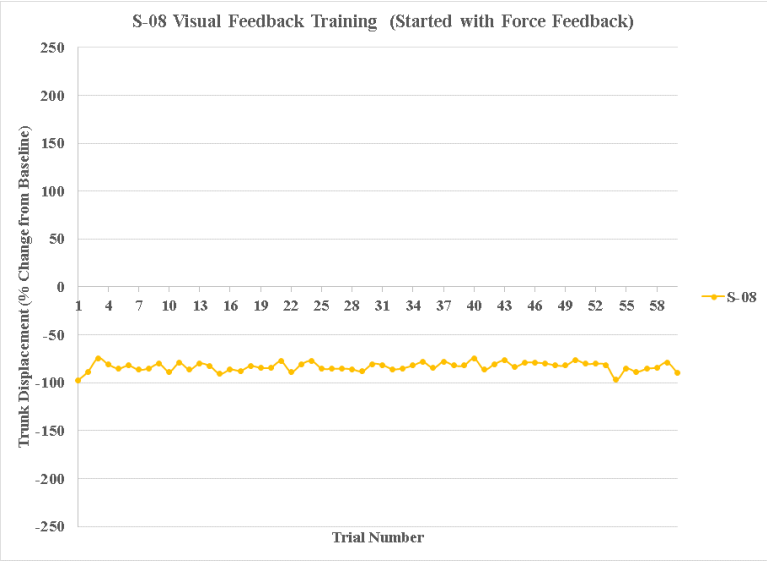

S-03 Force Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-03

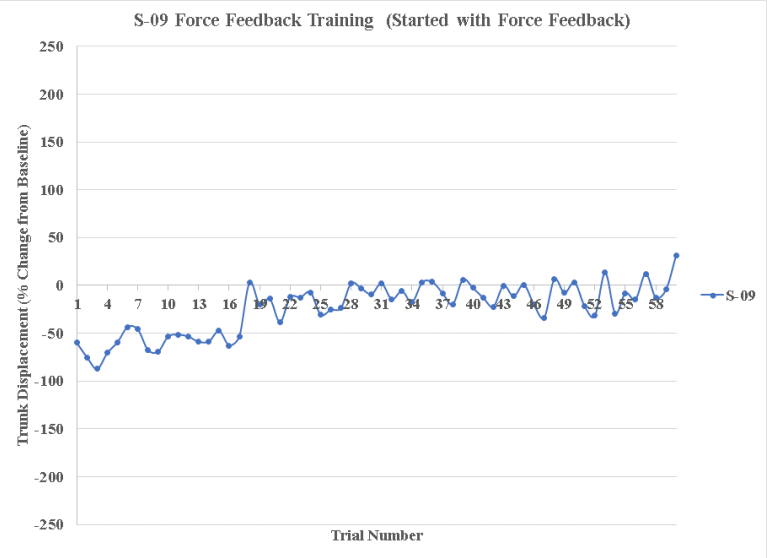

S-03 Visual Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-03

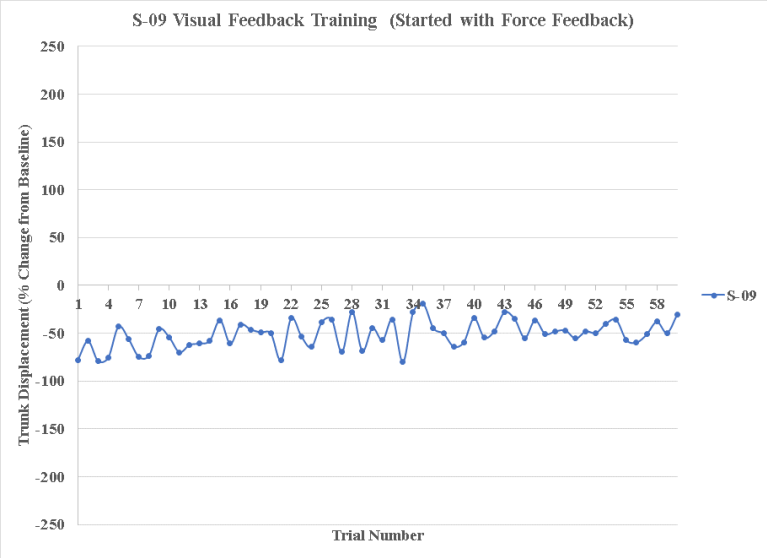

S-05 Force Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-05

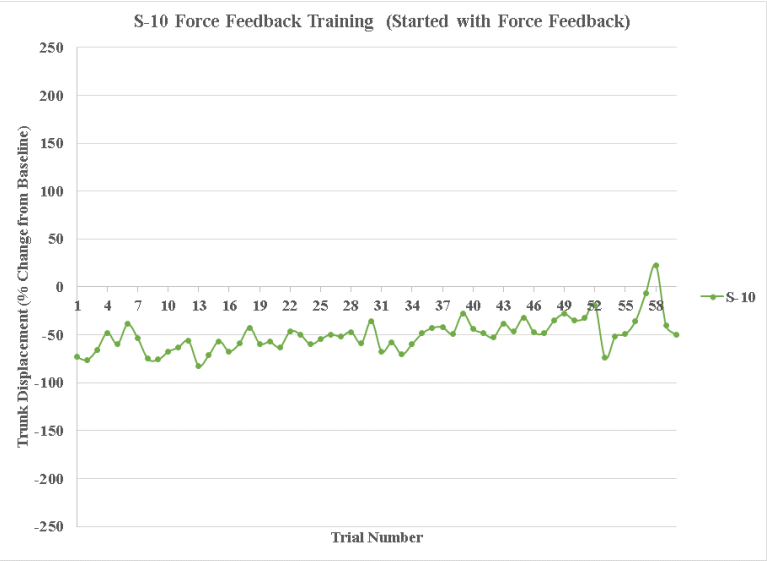

S-05 Visual Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-05

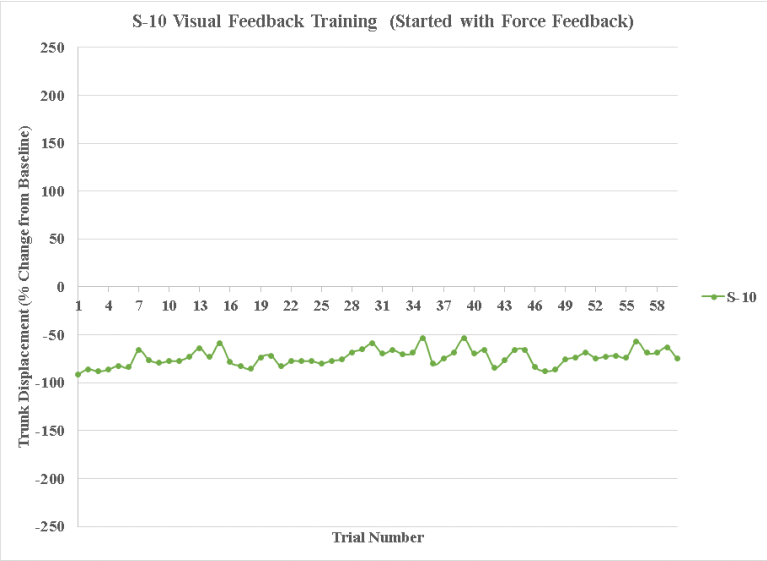

S-08 Force Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-08

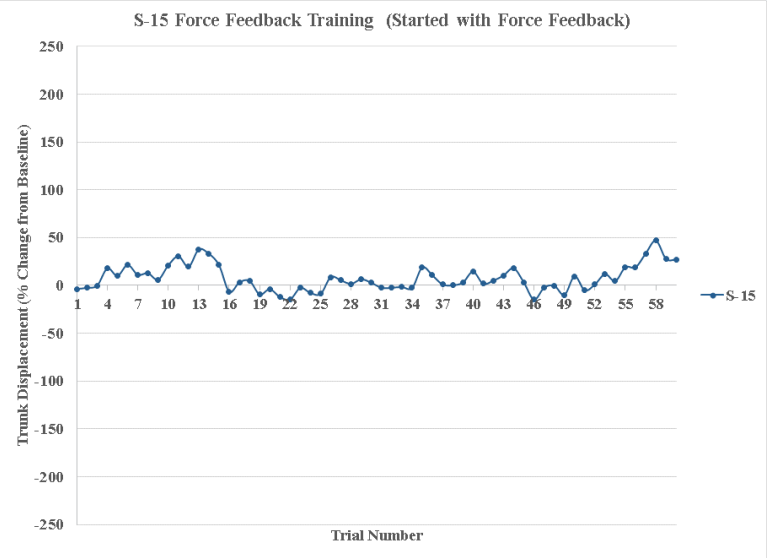

S-08 Visual Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-08

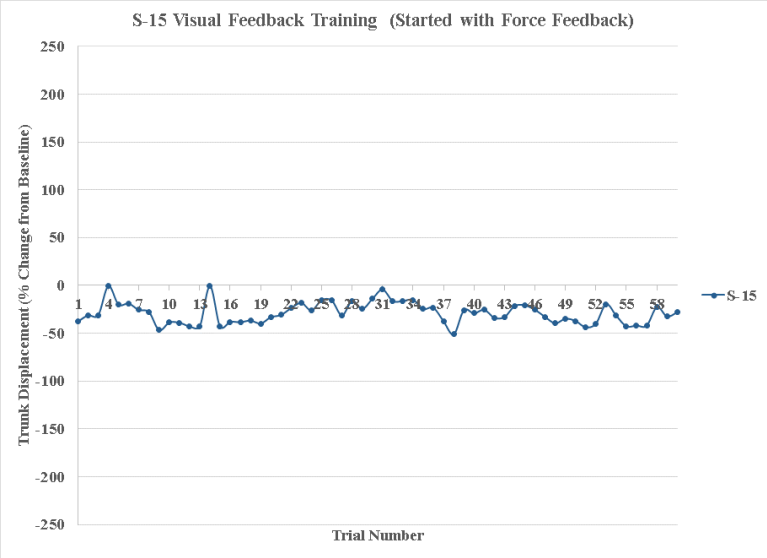

S-09 Force Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-09


S-09 Visual Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-09


S-10 Force Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-10


S-10 Visual Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-10


S-15 Force Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-15


S-15 Visual Feedback Training (Started with Force Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-15

Appendix E Chapter 4 Post-Test Questionnaire

This appendix presents the post-test questionnaire and results from Chapter 4. The questionnaire was administered at the end of the intervention.

E.1 Post-Test Questionnaire

Date:_____ **Participant Number:** _____

RIS (Reaching in Stroke)

Phase 3 Post-Test Questionnaire: Stroke Survivors

1. **Sex (circle one):** Male Female
2. **Age:** _____
3. **Height:** _____
4. **Dominant hand before stroke (circle one):** Left Right
5. **Weaker side of my body (circle one):** Left Right
6. **Site of Stroke:** _____
7. **Type of Stroke (please circle):** Hemorrhagic Ischemic
8. **Time since stroke:** _____
9. **Therapy services I receive:**_____
10. **How often do you receive therapy?** _____

Date:_____ **Participant Number:** _____

We would like your feedback on your experience trying the RIS system.

For the following statements, please circle the answer that best represents how strongly you feel about each statement.

A. Reaching Task:

1. **It was easy to control the cursor with my strong hand:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **It was easy to control the cursor with my weak hand:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **I felt tired after completing the session:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

4. **It was difficult to reach the targets:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ **Participant Number:** _____

5. **To be able to reach the targets, I had to move my trunk:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

B. Visual + Force Feedback alone (i.e., no game scores were given, you only saw the cursor filling up with red ink, and you felt the robots resisting your movement):

1. **It was difficult to understand the Visual+Force feedback**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **It was difficult to see the Visual (red ink filling up) feedback**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **It was difficult to feel the Force feedback (robots resisting your movement)**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

4. **When I received visual+force feedback I reduced how much I was moving my trunk**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

C. Scores+Visual+Force Feedback (i.e game scores were given, and you saw the cursor filling up with red ink, and you felt the robots resisting your movement):

1. **It was difficult to understand the Scores+Visual+Force feedback**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **It was difficult to see the Game Scores (Points that you got as a reward)**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **It was difficult to see the Visual (red ink filling up) feedback**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

4. **It was difficult to feel the Force feedback (robots resisting your movement)**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

5. **When I received Scores+Visual+Force feedback I reduced how much I was moving my trunk**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

D. Feedback Comparison:

1. **To reduce my trunk movements I would prefer to receive (select only one):**

Visual+Force feedback	Scores+Visual+ Force feedback	None	Only Visual feedback	Only Force feedback	Only Scores	Other

Why (please answer)?

_____

_____

_____

In addition, if you answered "other" please tell us what you meant by "other":

_____

_____

Date:_____ Participant Number: _____

E. System Design:

1. **The robotic devices limited my reaching movements:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **I felt comfortable grasping the robotic devices:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **The robotic devices felt heavy in my hands:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

4. **I felt unsafe using the robotic devices:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

5. **I would use these robotic devices for rehabilitation:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

6. **It was hard for me to see the targets and cursor on the computer's monitor:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

7. **I felt comfortable maintaining a proper seated posture:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ **Participant Number:** _____

F. System Usability Scale (SUS): © Digital Equipment Corporation, 1986.

In the following statements, "**system**" refers to the target game and the robotic devices. Please circle the number that best represents how strongly you feel about each statement.

1. **I think that I would like to use this system frequently:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

2. **I found the system unnecessarily complex:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

3. **I thought the system was easy to use:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

4. **I think that I would need the support of a technical person to be able to use this system:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

5. **I found the various functions in this system were well integrated:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

6. **I thought there was too much inconsistency in this system:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

7. **I would imagine that most people would learn to use this system very quickly:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

8. **I found the system very cumbersome to use:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

9. **I felt very confident using the system:**

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ **Participant Number:** _____

10. I needed to learn a lot of things before I could get going with this system:

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

Date:_____ Participant Number: _____

G. System's Features:

1. **Please complete the following sentence: "My favorite features of this system were..."**

_____

_____

_____

2. **Please complete the following sentence: "My least favorite features of this system were..."**

_____

_____

_____

3. **Is there anything that you would change about the system?**

_____

_____

_____

Thank you for your participation!

E.2 Post-Test Questionnaire Results

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

BIOFEEDBACK VS. GAME SCORES FOR REDUCING TRUNK COMPENSATION IN STROKE SURVIVORS: A RANDOMIZED CROSSOVER TRIAL

POST-TEST QUESTIONNAIRE RESULTS

BULMARO A. VALDÉS, H.F. MACHIEL VAN DER LOOS

Collaborative Advanced Robotics
and Intelligent Systems Laboratory

POST-TEST QUESTIONNAIRE PART A (REACHING TASK)

Part A of the Post- Test Questionnaire:

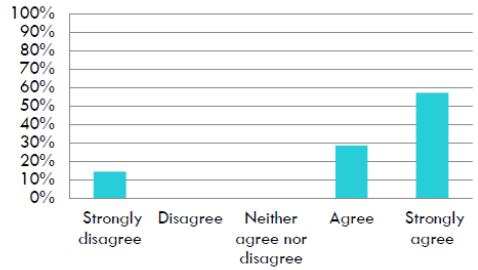
- Likert Scale comprised of 4 Likert-type questions (A.1-A.4)
- Examined the underlying belief that: "The level of difficulty of the reaching task was adequate for stroke survivors"

	Part A
Average	3.48
SD	0.73

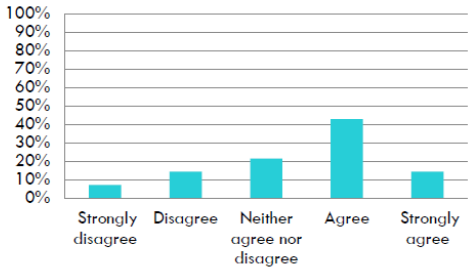
On average people agreed that the level of difficulty of the reaching task was adequate for stroke survivors.
T-test against neutral response, *t*(13)=2.47, *p*=0.028*, *d*= 0.66, *95%CI* (3.06, 3.9)

POST-TEST QUESTIONNAIRE PART A (REACHING TASK) A.1-A.4

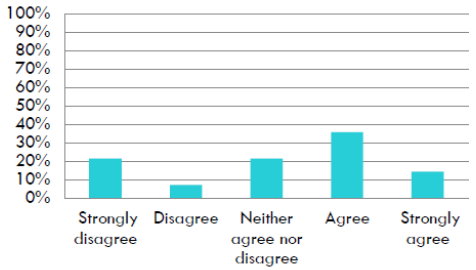
A.1 It was easy to control the cursor with my strong hand



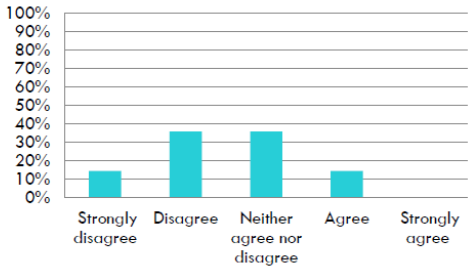
A.2 It was easy to control the cursor with my weak hand



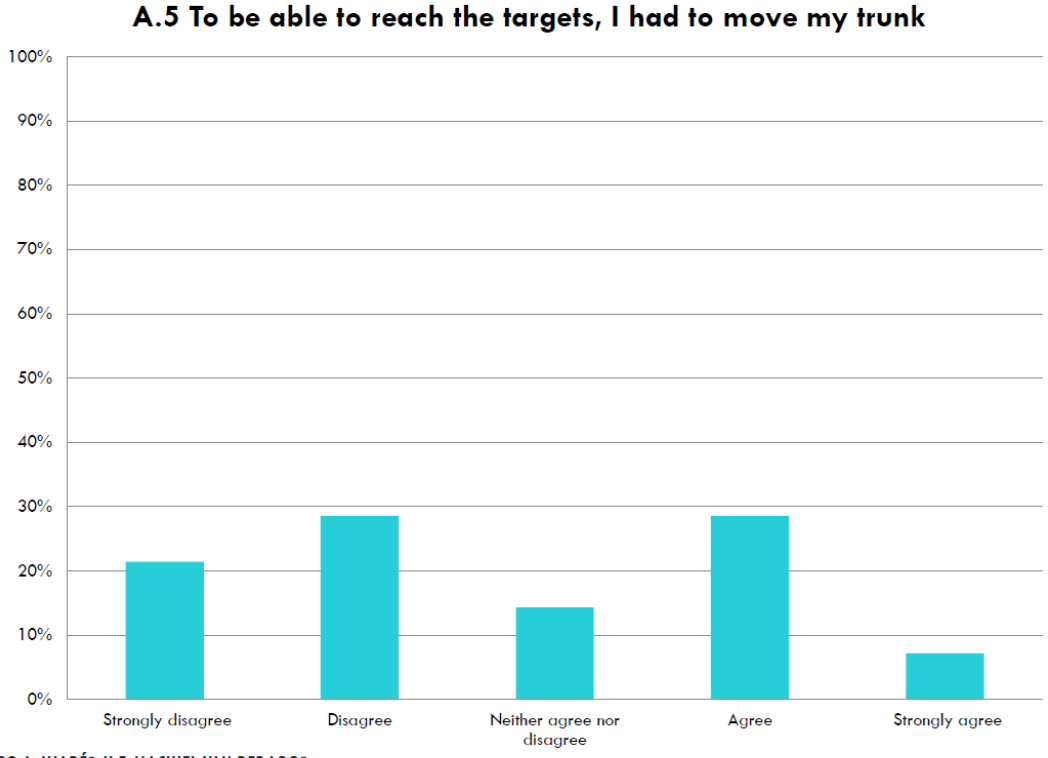
A.3 I felt tired after completing the session



A.4 It was difficult to reach the targets



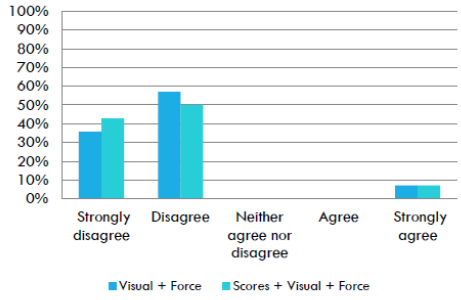
POST-TEST QUESTIONNAIRE PART A (REACHING TASK) A.5



Combined categories:
36% Agree
14% Neutral
50% Disagree

POST-TEST QUESTIONNAIRE PART B & C (FEEDBACK)

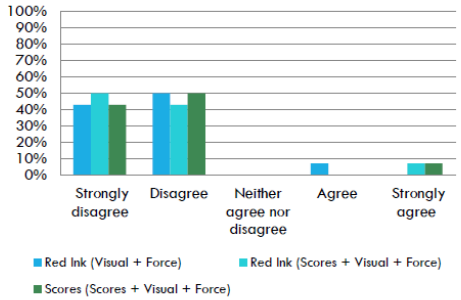
B.1& C.1 It was difficult to understand the feedback



Mode		
Visual + Force	2	Disagree
Scores + Visual + Force	2	Disagree

Feedbacks not difficult to understand.

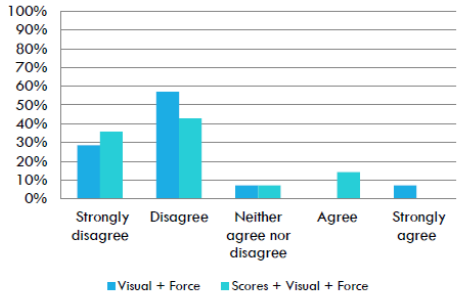
B.2, C.2 & C.3 It was difficult to see the visual feedback



Mode		
Visual + Force (Red ink)	2	Disagree
Scores + Visual + Force (Red ink)	1	Strongly Disagree
Scores + Visual + Force (Scores)	2	Disagree

Visual feedback (red ink) and Scores not difficult to perceive.

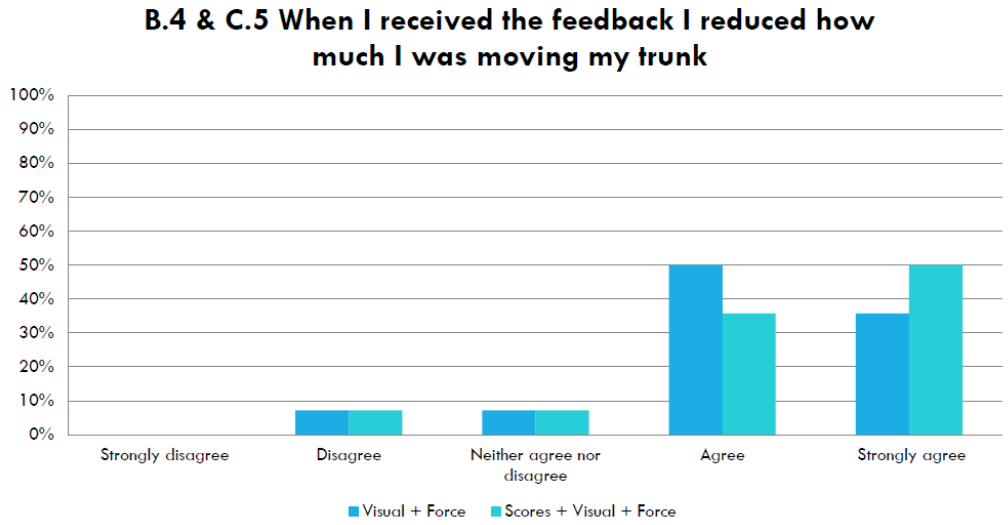
B.3 & C.4 It was difficult to feel the force feedback



Mode		
Visual + Force	2	Disagree
Scores + Visual + Force	2	Disagree

Force feedback not difficult to perceive.

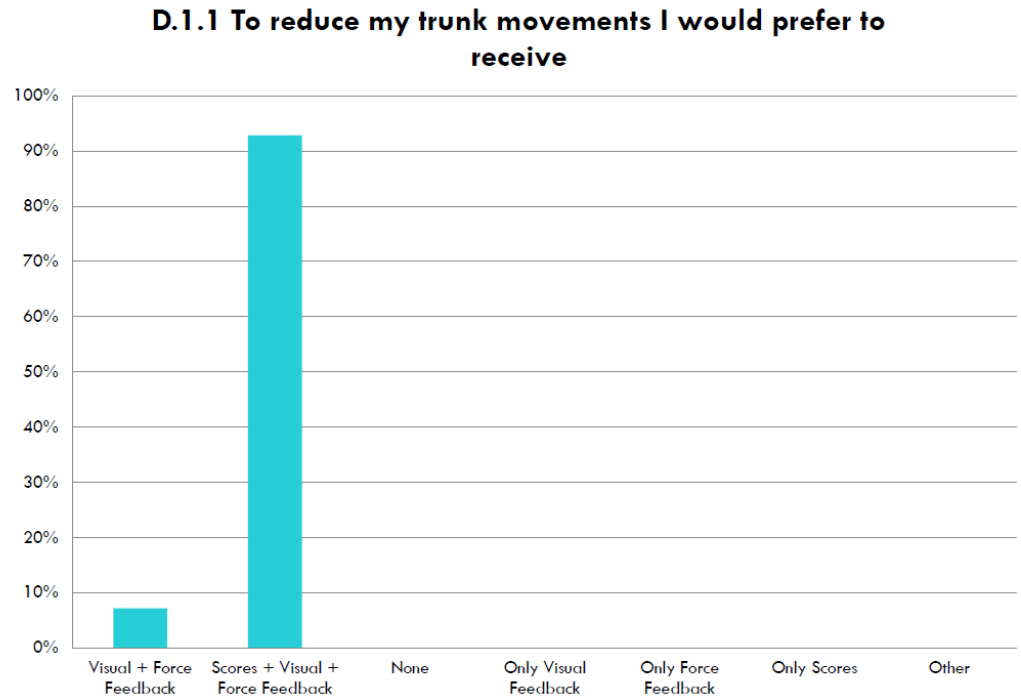
POST-TEST QUESTIONNAIRE PART B & C (FEEDBACK)



Mode		
Visual + Force	4	Agree
Scores + Visual + Force	5	Strongly Agree

Both feedback conditions reduced compensation

POST-TEST QUESTIONNAIRE PART D (FEEDBACK COMPARISON)



POST-TEST QUESTIONNAIRE PART D (FEEDBACK COMPARISON)

For the ones that answered "Scores + Visual + Force":

- *"Easy to figure out how it worked"*
- *"It is important to receive all feedback conditions to do a better job in the task"*
- *"I can see the monitor (scores and red ink)"*
- *"Very encouraging, helps you concentrate, competition is good"*
- *"It helps to get feedback on my movements because I don't always realize that I am doing something. It helps me improve the next time when I get feedback"*
- *"Felt like you were playing a game helps want to achieve a higher score"*
- *"Easy to understand. Good to keep track with scores"*
- *"It is normal and is easy to understand"*
- *"See your movement"*
- *"Like scores, more motivated"*
- *"Motivates you to get better scores"*
- *"I can see my improvement based on the red ink+force+scores. Scores gives me encouragement to do well"*
- *"Easy to see"*

For the one that answered "Visual + Force":

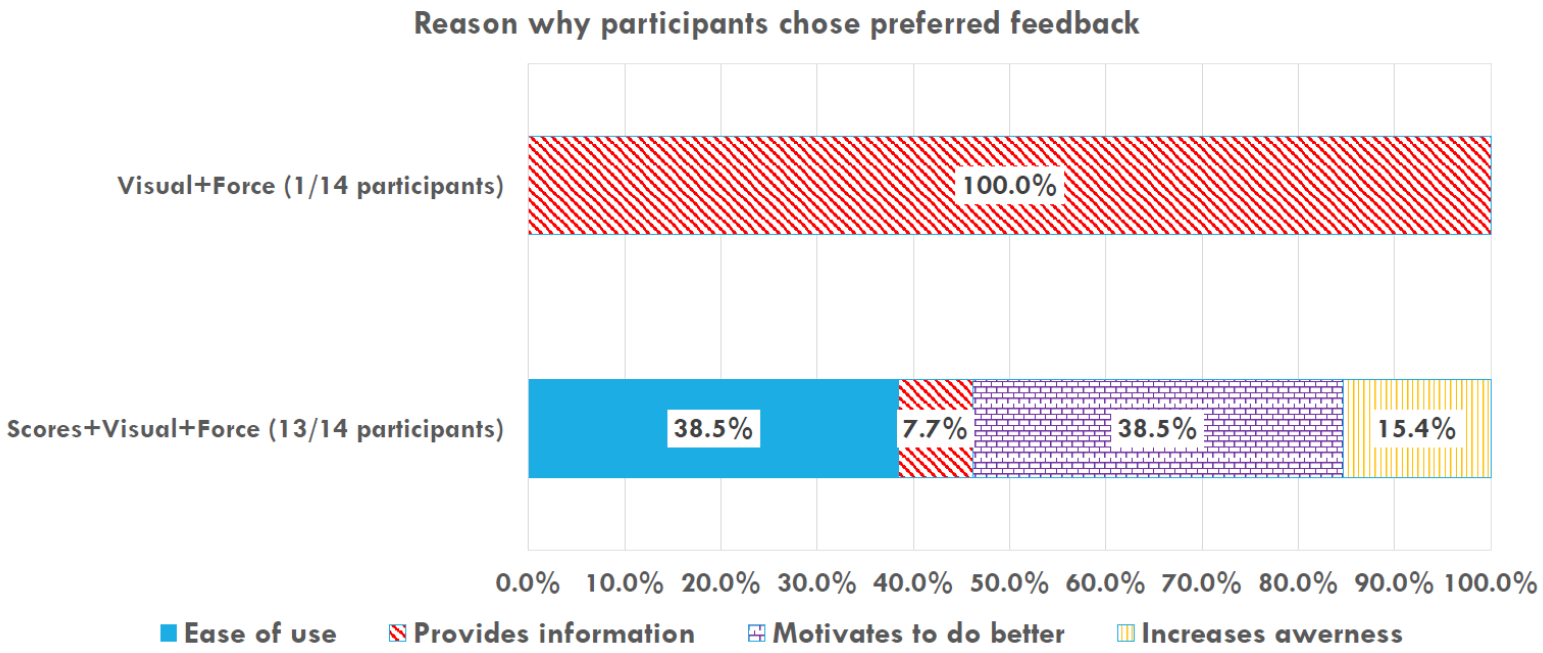
- *"Because I got the feedback in the direction I was moving"*

POST-TEST QUESTIONNAIRE PART D (FEEDBACK COMPARISON), CONTENT ANALYSIS

For participants (14/14) who answered why they chose a specific type of feedback to reduce their trunk compensation, the main reasons they gave were:

- **Ease of use:** The feedback was easy to understand, perceive, and worked well.
- **Provides information:** The feedback provided movement information to participants.
- **Motivates to do better:** The feedback motivated participants to perform better by providing them with the opportunity to play in a game-like scenario, compete, and track their progress using game scores.
- **Increases awareness**: The feedback increased the participants' awareness of their trunk compensation levels and arm movements.

POST-TEST QUESTIONNAIRE PART D (FEEDBACK COMPARISON), CONTENT ANALYSIS



POST-TEST QUESTIONNAIRE PART E (SYSTEM DESIGN) E.1-E.7

Part E of the Post- Test Questionnaire:

- Likert Scale comprised of 7 Likert-type questions (E.1-E.7)
- Examined the underlying belief that: "the system's design is appropriate for performing reaching movements for rehabilitation"

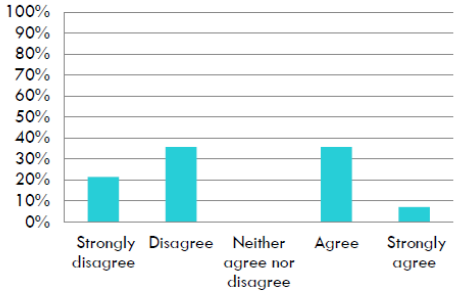
	Part E
Average	4.07
SD	0.49

On average people agreed that system was appropriate for performing reaching movements for rehabilitation.

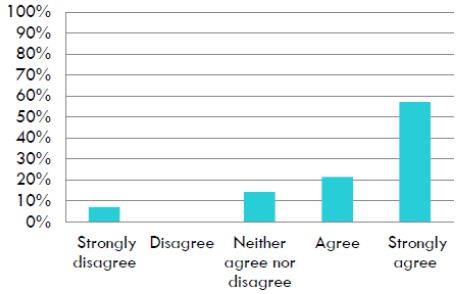
T-test against neutral response, $t(13)=8.17$, $p=0.000$*, $d=2.18$, $95\%CI$ (3.79, 4.35)**

POST-TEST QUESTIONNAIRE PART E (SYSTEM DESIGN) E.1-E.3

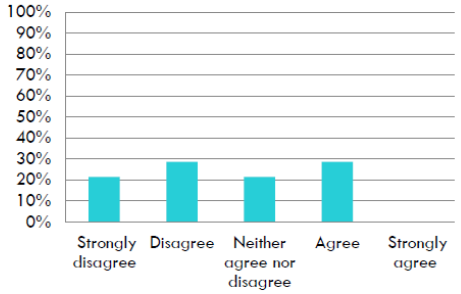
E.1 The robotic devices limited my reaching movements



E.2 I felt comfortable grasping the robotic devices

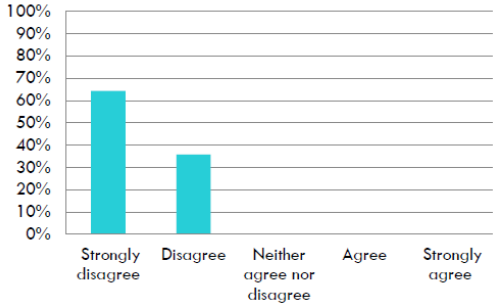


E.3 The robotic devices felt heavy in my hands

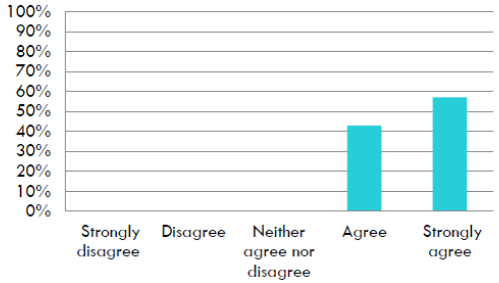


POST-TEST QUESTIONNAIRE PART E (SYSTEM DESIGN) E.4-E.7

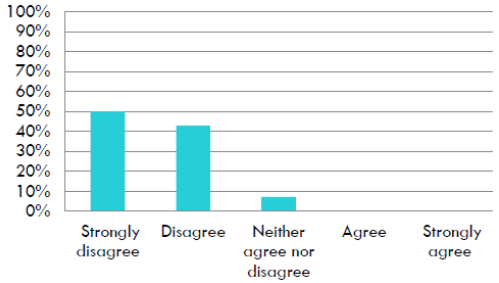
E.4 I felt unsafe using the robotic devices



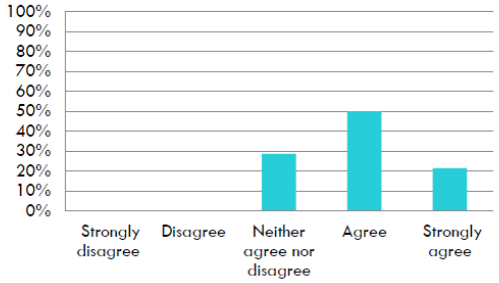
E.5 I would use these robotic devices for rehabilitation



E.6 It was hard for me to see the targets and cursor on the computer's monitor



E.7 I felt comfortable maintaining a proper seated posture



POST-TEST QUESTIONNAIRE PART F (SUS) F.1-F.10

System Usability Scale (SUS): "A reliable, low-cost usability scale that can be used for global assessments of systems usability".[1]

- It consists of a 10 item questionnaire with five response options for respondents
- **A value above 68 is considered above average. Though the scores are 0-100, these are not percentages.**
- Adjective ratings are[2]: "Worst Imaginable", "Awful", "Poor", "OK", "Good", "Excellent", and "Best Imaginable".

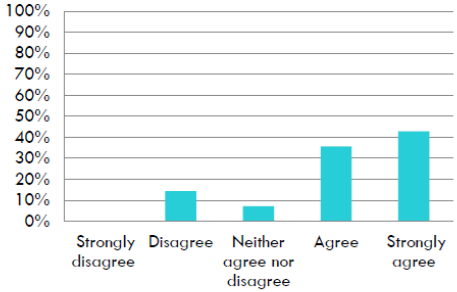
	SUS Score
Average	73
SD	15

On average system can be considered "Good"

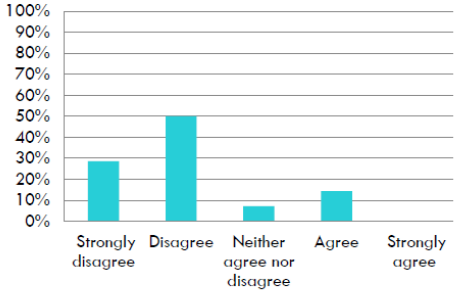
[1] Brooke J. SUS-A quick and dirty usability scale. In: Usability evaluation in industry. 1996. p. 4–7.
[2] Bangor A, Kortum P, Miller J. Determining what individual SUS scores mean: Adding an adjective rating scale. Journal of usability studies. 2009;4(3):114–123.

POST-TEST QUESTIONNAIRE PART F (SUS) F.1-F.3

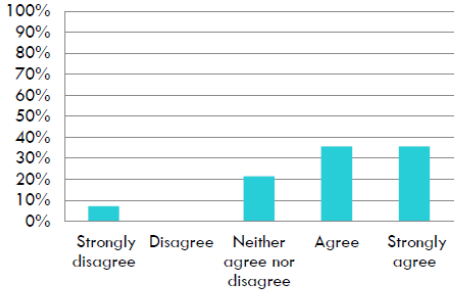
F.1 I think that I would like to use this system frequently



F.2 I found the system unnecessarily complex

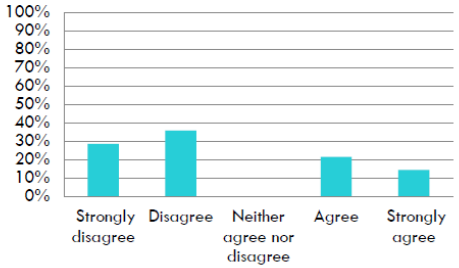


F.3 I thought the system was easy to use

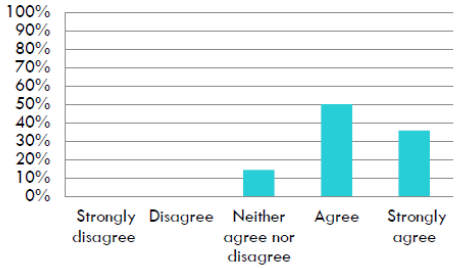


POST-TEST QUESTIONNAIRE PART F (SUS) F.4-F.6

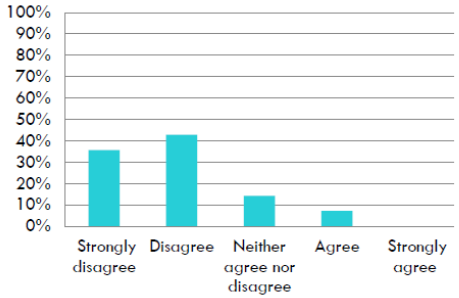
F.4 I think that I would need the support of a technical person to be able to use this system



F.5 I found the various functions in this system were well integrated

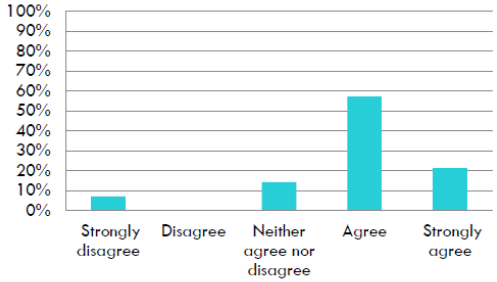


F.6 I thought there was too much inconsistency in this system

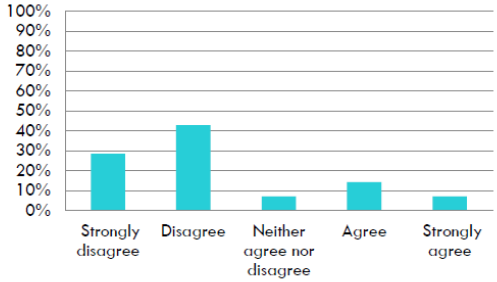


POST-TEST QUESTIONNAIRE PART F (SUS) F.7-F.10

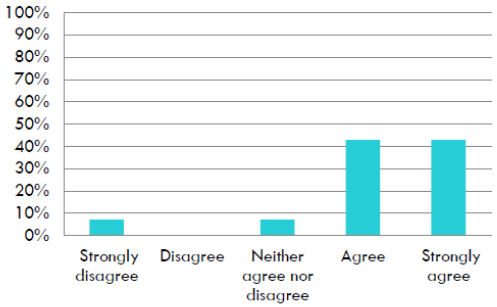
F.7 I would imagine that most people would learn to use this system very quickly



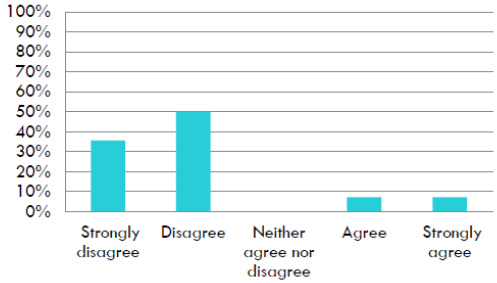
F.8 I found the system very cumbersome to use



F.9 I felt very confident using the system



F.10 I needed to learn a lot of things before I could get going with this system



POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.1-G.3

G.1 My favorite features:

- "Hitting the targets"
- "Getting feedback about compensation with scores + force + visual"
- "I liked the scores"
- "Instructor"
- "It makes exercising easy + fun. It helps me think about moving in a productive way"
- "The colors and scoring ability. The feeling of achievement when completing task"
- "Achieving the goal at the end of the line. Red ink is good to see; help me control trunk movement"
- "The game in the screen"
- "All of it is pretty good"
- "The cursor movement"
- "The scoring system, cumulative scores. Improve, motivated, and more fun"
- "The use of robotic device helps encourage reaching further. Helpful to prevent trunk movement (encourage arm use)"
- "The robotic arms because it forces me to use my left (affected) arm"
- "Scores, easy to see"

G.2 My least favorite features:

- Nothing
- "When you take out the feedback"
- Nothing
- None
- "I can't use it daily!"
- "Long trial"
- None
- "It was hard for my hand"
- "Pretty fine with the entire system (none)"
- "Sometimes it was hard to control"
- "Getting back into original position. Time consuming and really difficult"
- "Didn't like using the strap"
- No
- Nothing

G.3 Anything that you would change:

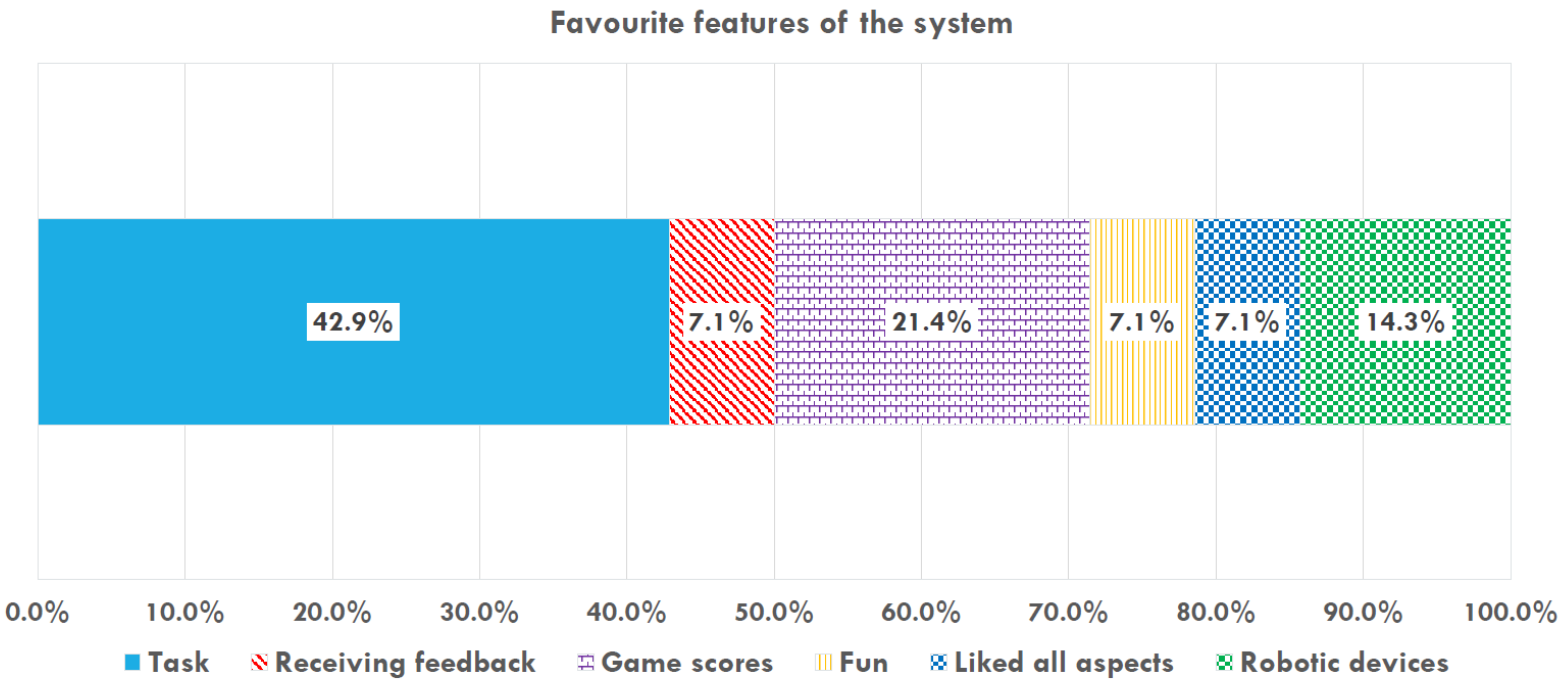
- Nothing
- "Improve the handle on the weak side because it can get uncomfortable with the straps and tape"
- Nothing
- No
- "Make it cheap and portable"
- "Try to get more people involved"
- Nothing
- "Something to help the affected hand move the robot"
- "This system is normal. You can't tell and pretty much fine"
- Nothing
- "Make it more fun, more animation like ping pong make it exciting"
- "Make the strap flexible softer. Would like to operate the system from her chair by herself (remote operation)"
- Nothing
- "Strap make it better"

POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.1, CONTENT ANALYSIS

For participants (14/14) who answered about their favourite features of the system, their main answers were:

- **Task:** Participants liked completing the reaching task by moving the cursors towards the target, as it gave them a feeling of achievement. They also liked receiving help from the research staff.
- **Receiving feedback:** Participants liked receiving feedback about their trunk compensation.
- **Game scores:** Participants liked accumulating points, which motivated them to do better.
- **Fun:** The system was fun to use.
- **Liked all aspects:** Participants liked all features of the system.
- **Robotic devices:** Participants liked using the system's robotic devices, which encouraged them to reach further and use their affected arm.

POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.1, CONTENT ANALYSIS

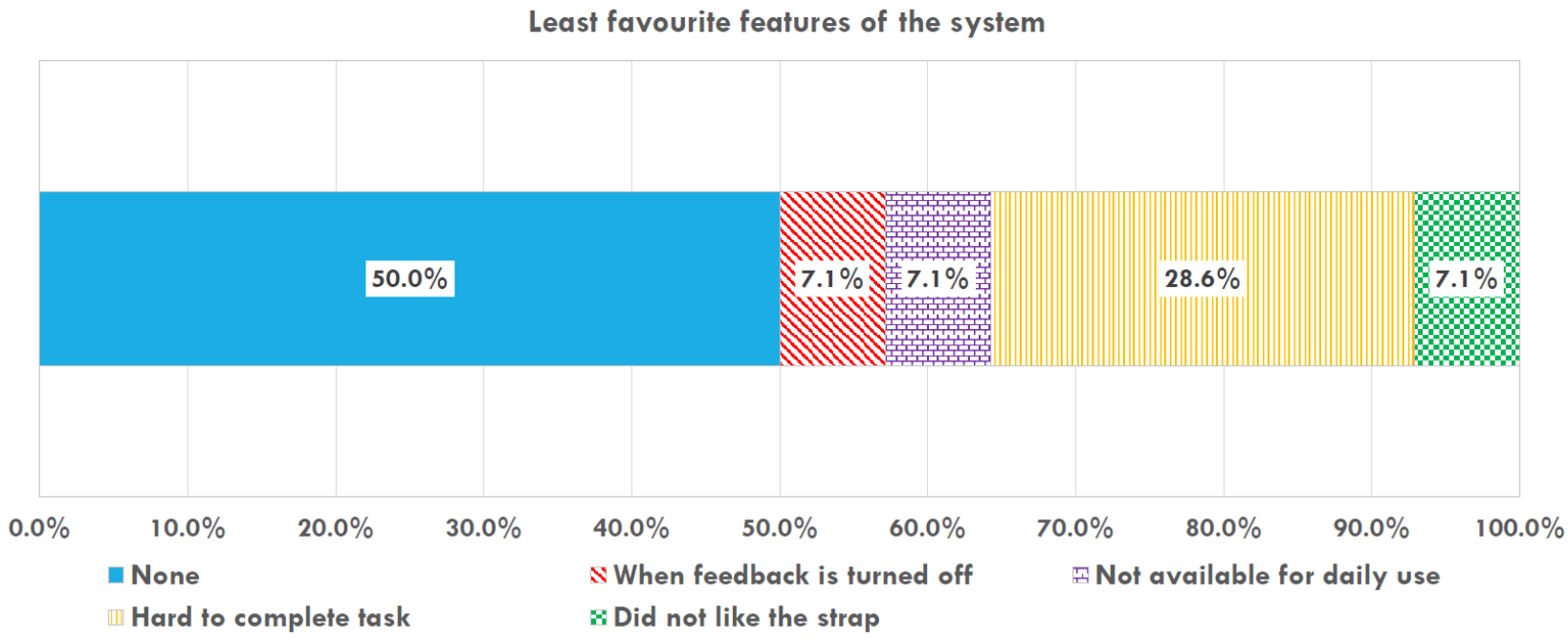


POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.2, CONTENT ANALYSIS

For participants (14/14) who answered about their least favourite features of the system, their main answers were:

- **None:** Participants liked all features of the system.
- **When feedback is turned off:** Participants did not like when they stopped receiving feedback about their trunk compensation.
- **Not available for daily use:** Participants would like to be able to use the system outside the research lab.
- **Hard to complete task:** Participants found that controlling the cursors by moving their hands and getting back to the calibrated initial position was hard. In addition, they felt that the trial was long.
- **Did not like the strap:** Participants did not like the strap that was used to secure their hands to the robot.

POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.2, CONTENT ANALYSIS

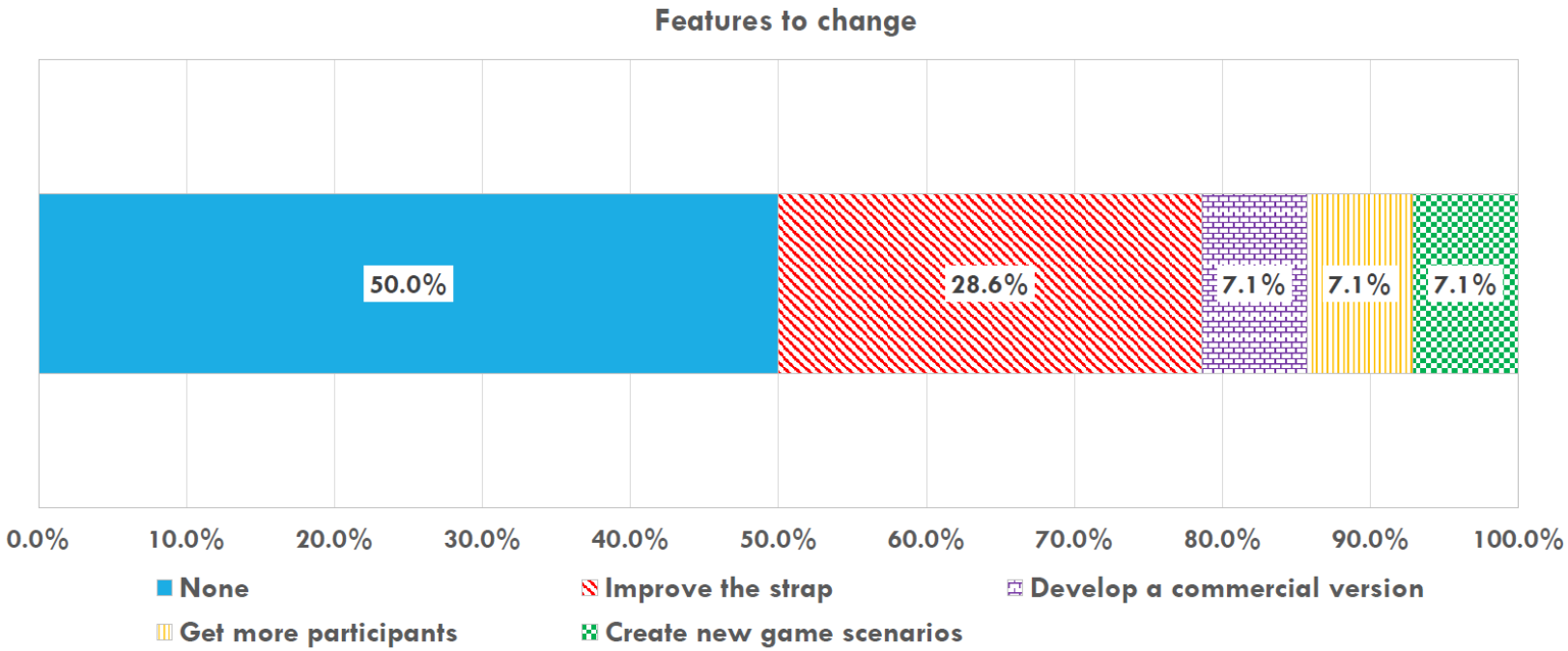


POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.3, CONTENT ANALYSIS

For participants (14/14) who answered if there was anything that they would change about the system, their main answers were:

- **None:** Participants did not want to change anything about the system.
- **Improve the strap:** Participants would like an improved version of the strap that secured their affected hands to the robot.
- **Develop a commercial version:** Participants would like an affordable and portable version of the system.
- **Get more participants:** Participants would like to have more people trying the system.
- **Create new game scenarios:** Participants would like to have new game scenarios to make the task more exciting and fun.

POST-TEST QUESTIONNAIRE PART G (SYSTEM'S FEATURES) G.3, CONTENT ANALYSIS

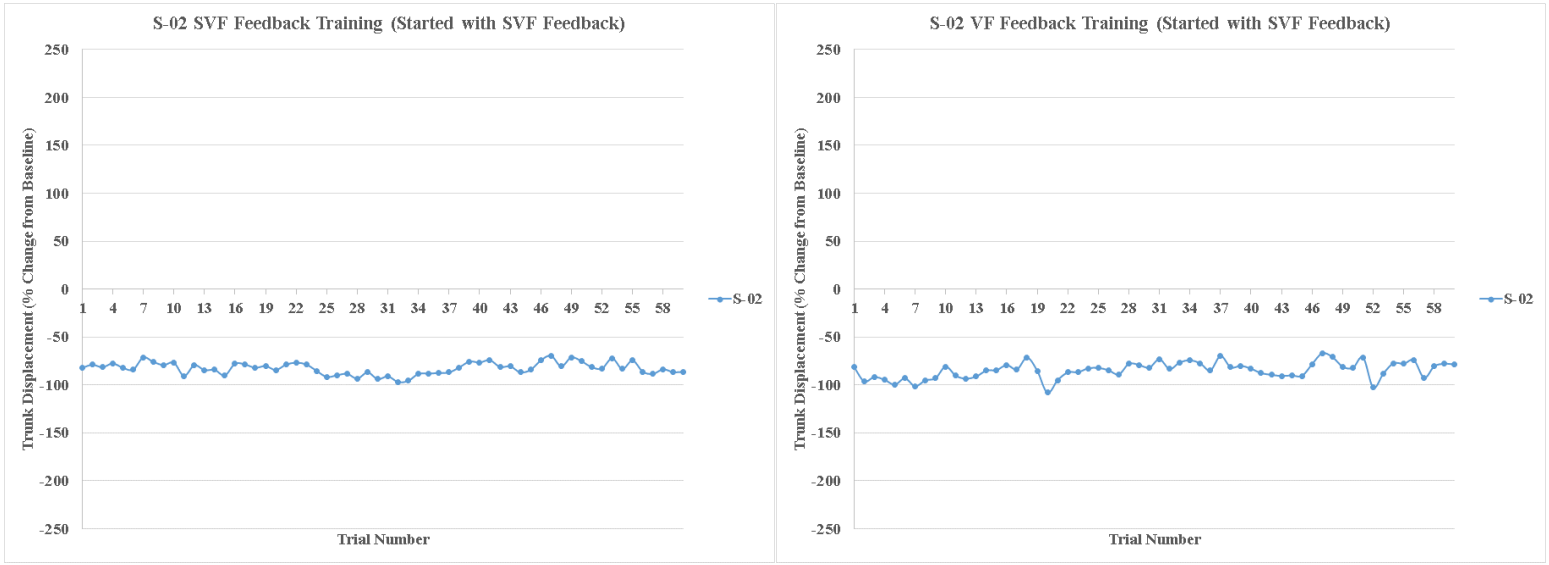


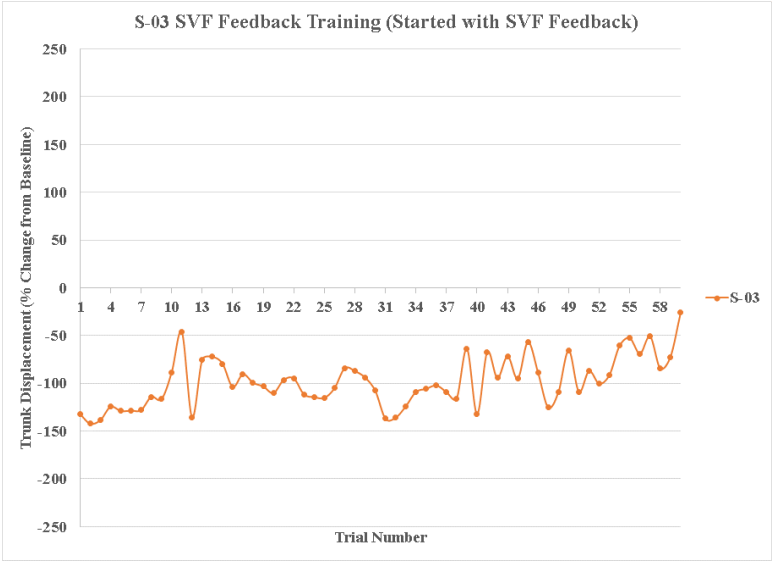
Appendix F Chapter 4 Participants' Trunk Displacement Data During Training Trials

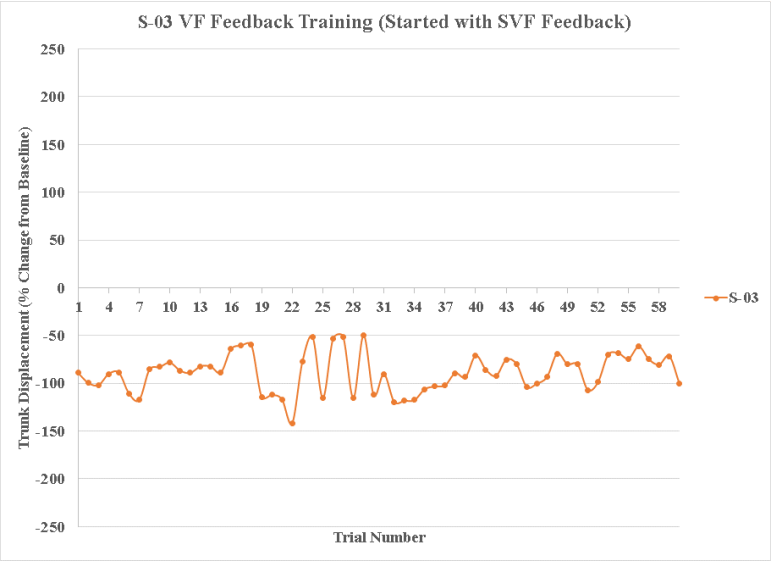
This appendix presents the individual trunk displacement data during the training trials when feedback was active.

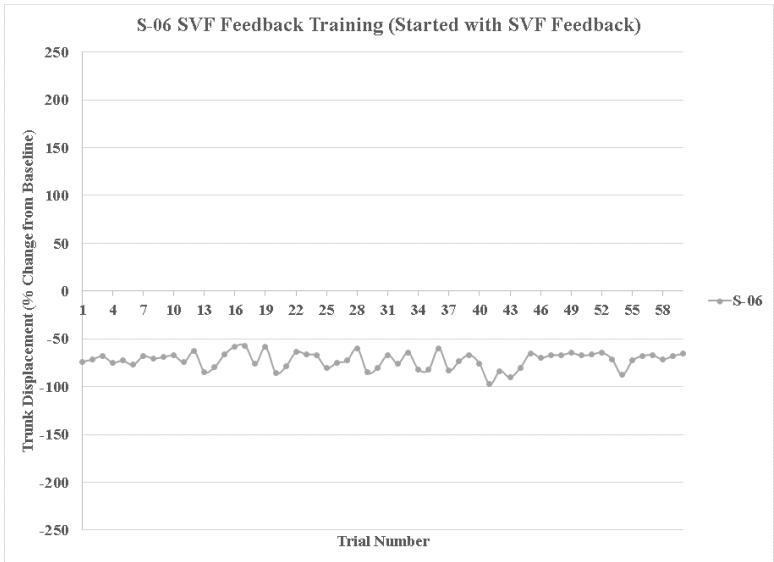
Scores+Visual+Force: SVF, and Visual+Force: VF.

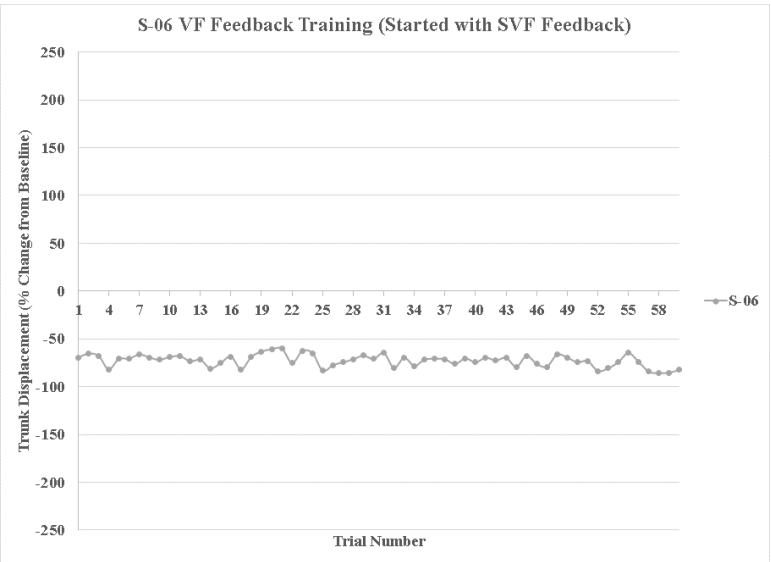
F.1 Participants who Started with SVF

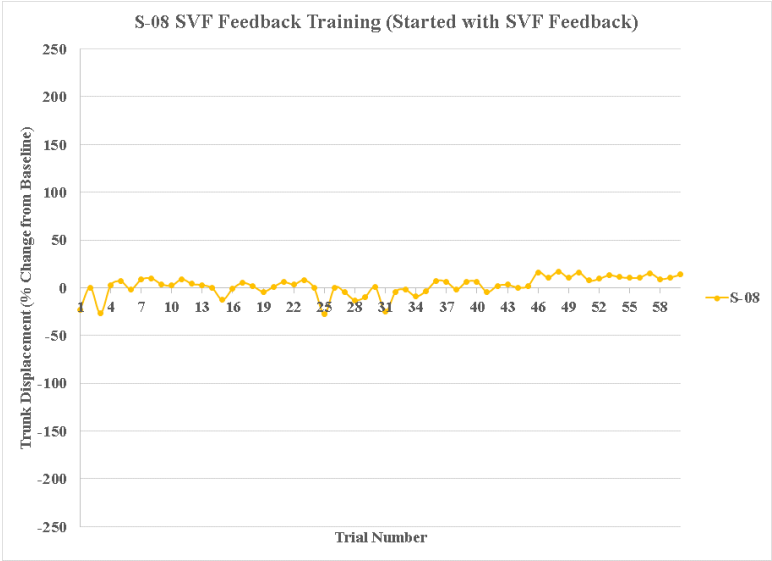


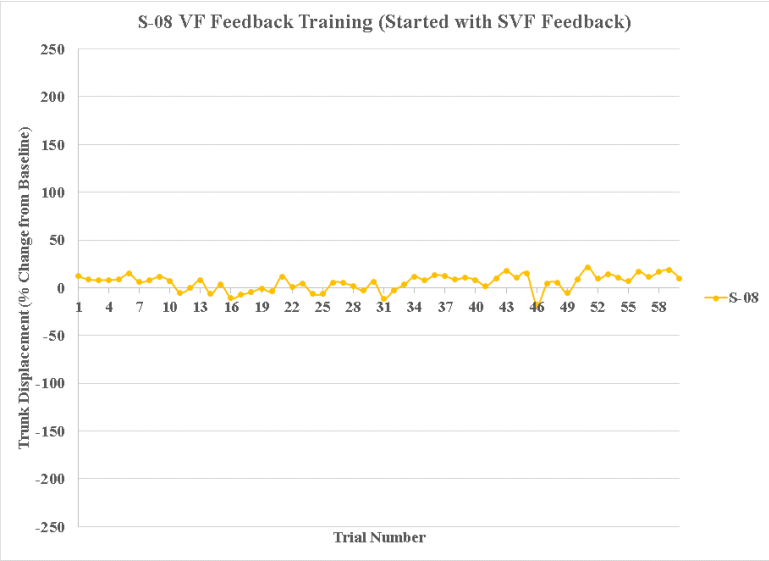

S-03 SVF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-03

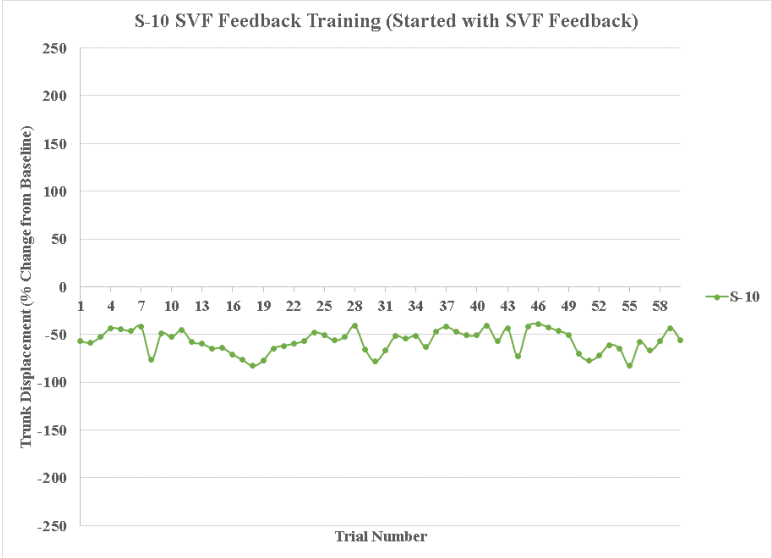

S-03 VF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-03

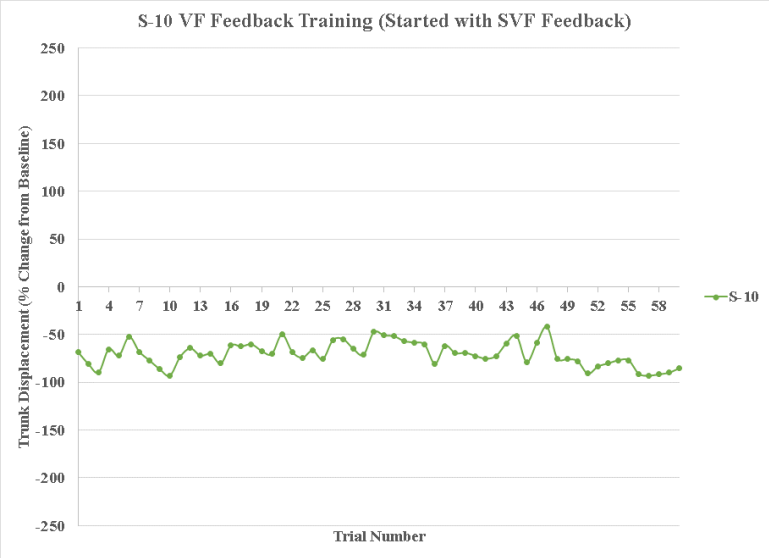

S-06 SVF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-06

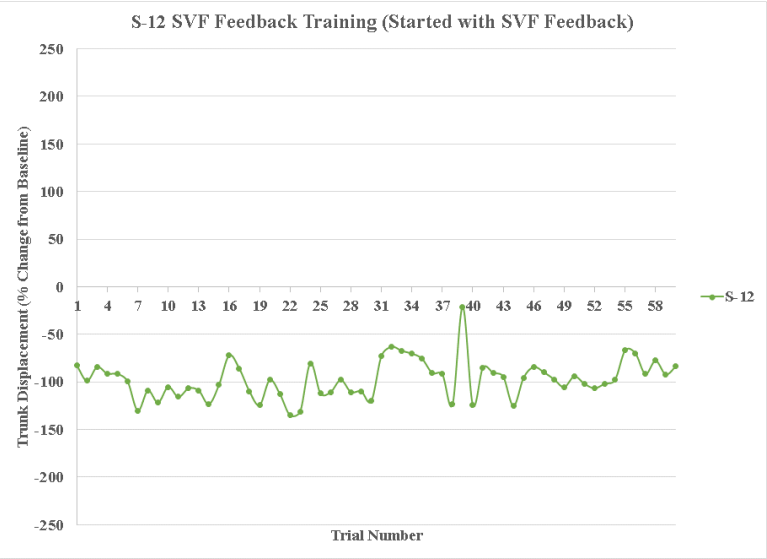

S-06 VF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
250
200
150
100
50
0
-50
-100
-150
-200
-250
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Trial Number
S-06

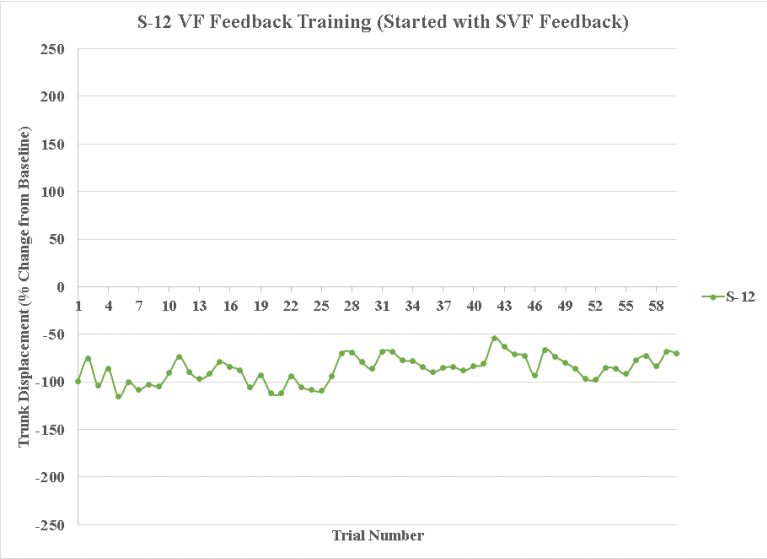

S-08 SVF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-08

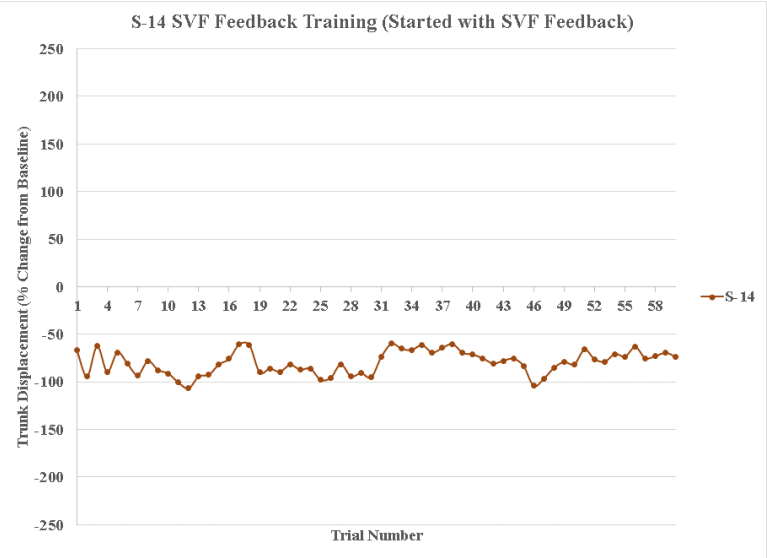

S-08 VF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-08

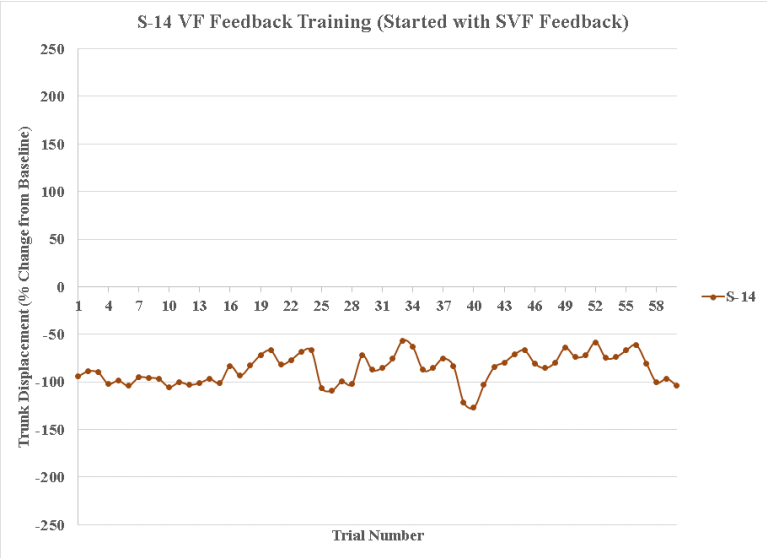

S-10 SVF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-10


S-10 VF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-10

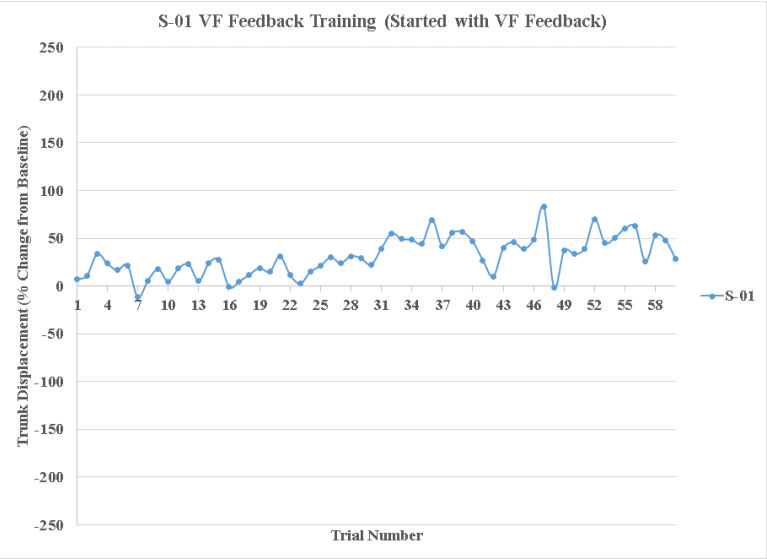

S-12 SVF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-12

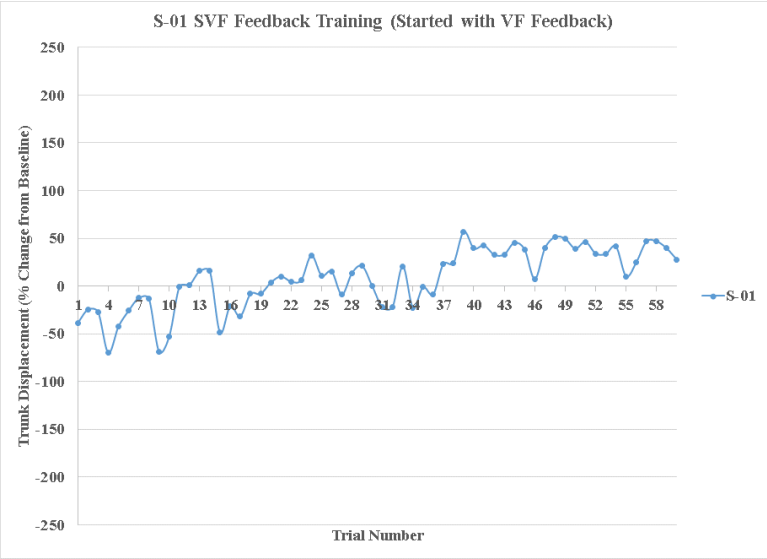

S-12 VF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-12

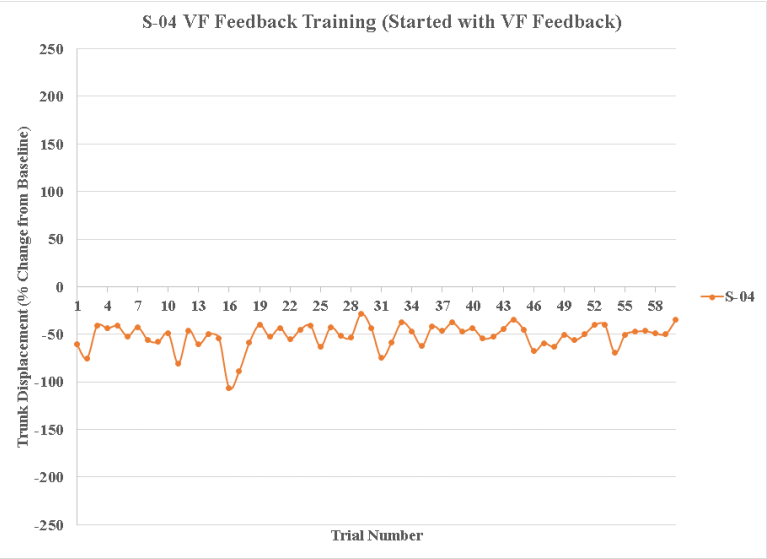

S-14 SVF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-14

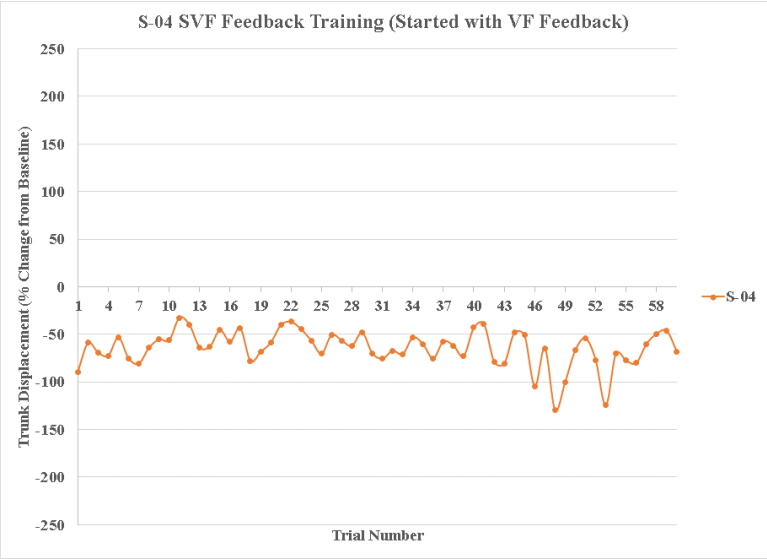

S-14 VF Feedback Training (Started with SVF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-14

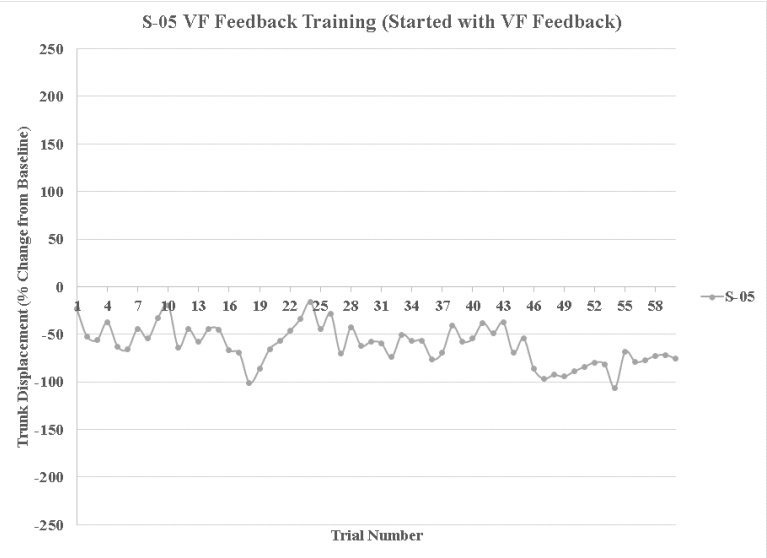
F.2 Participants who Started with VF

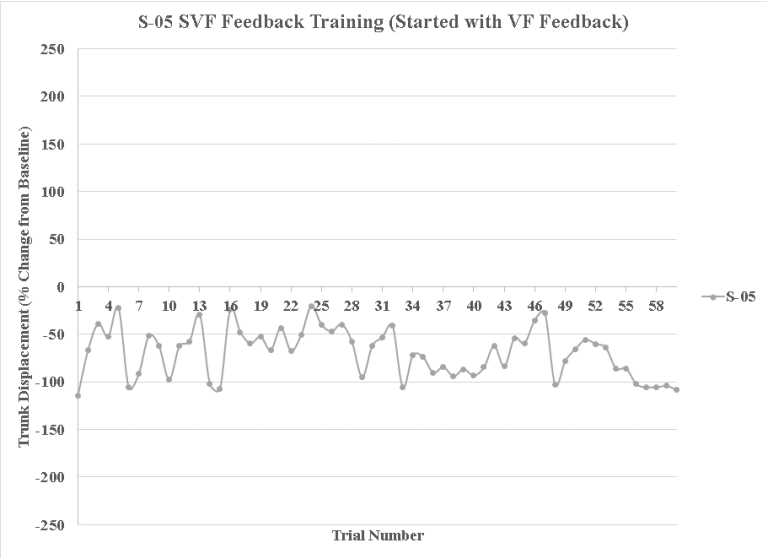


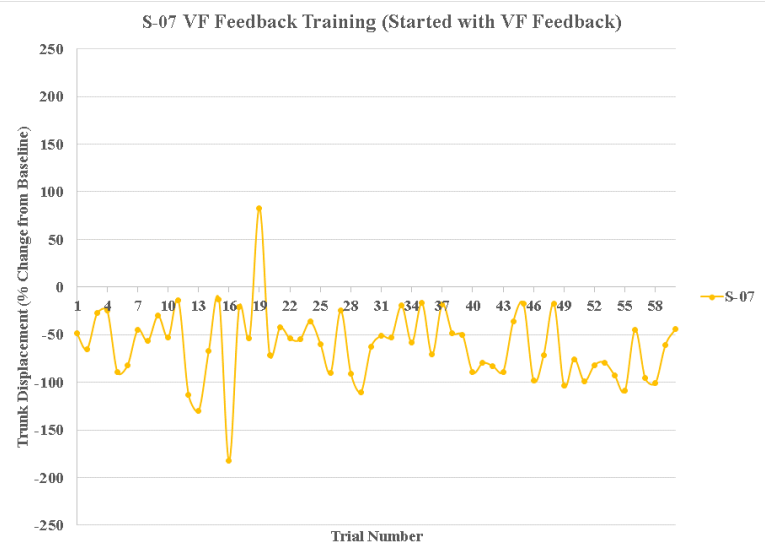


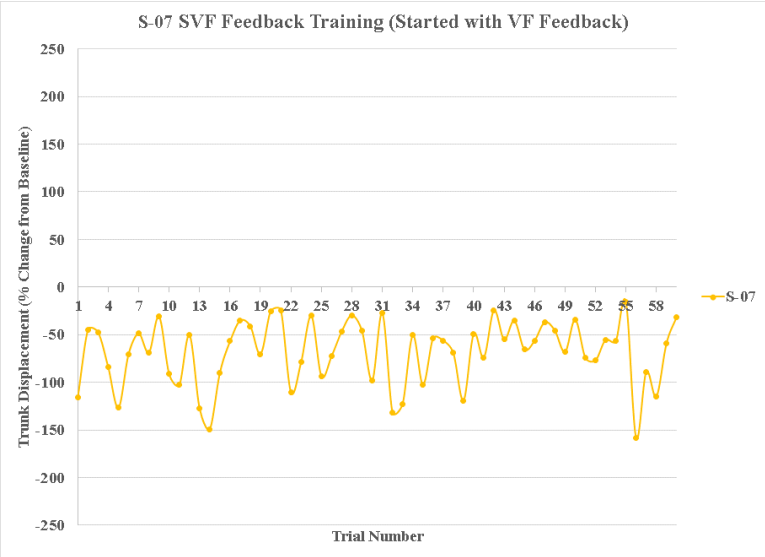

S-04 VF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-04


S-04 SVF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-04


S-05 VF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-05


S-05 SVF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-05


S-07 VF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-07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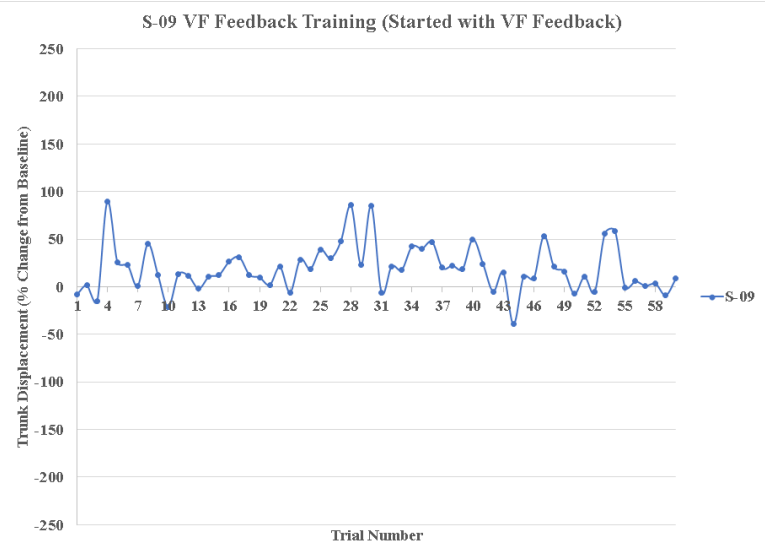
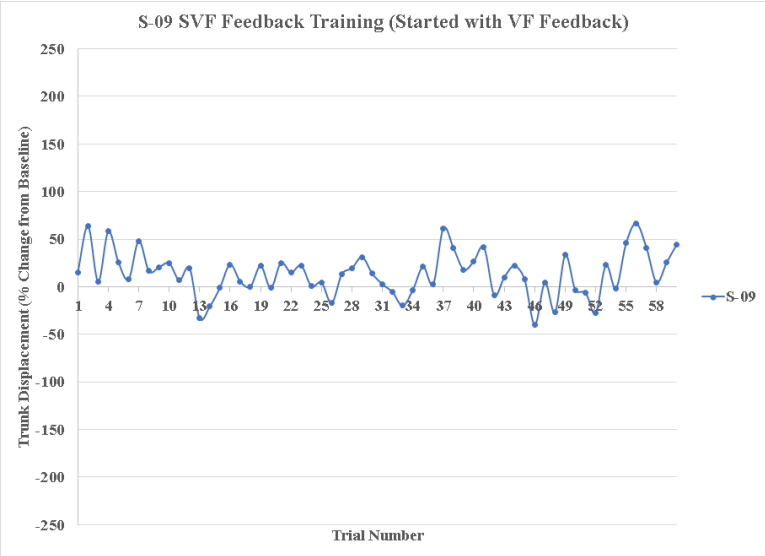
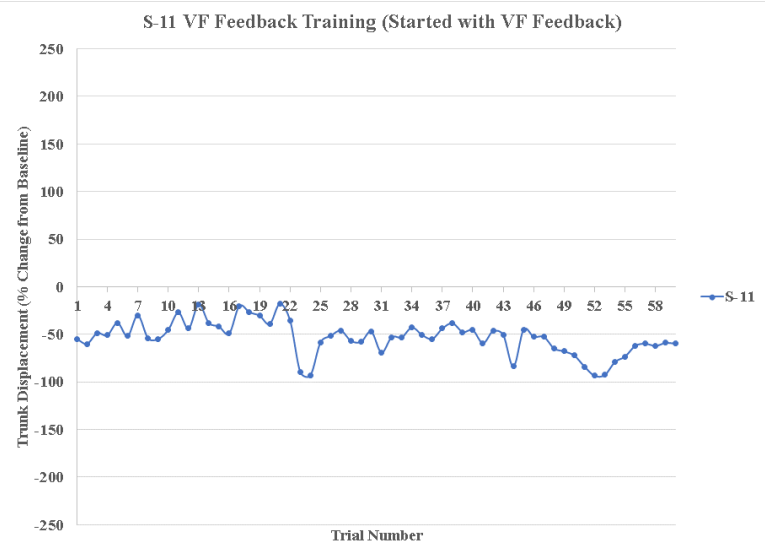
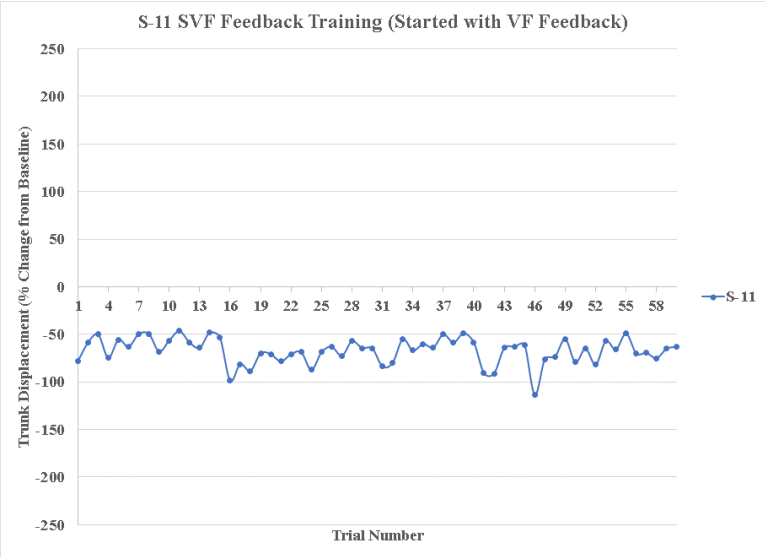
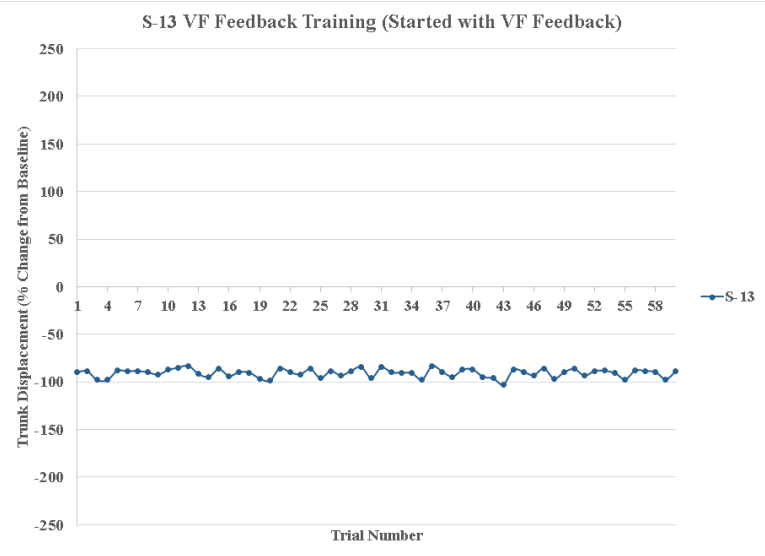
Trunk Displacement (% Change from Baseline)
Trial Number
S-07

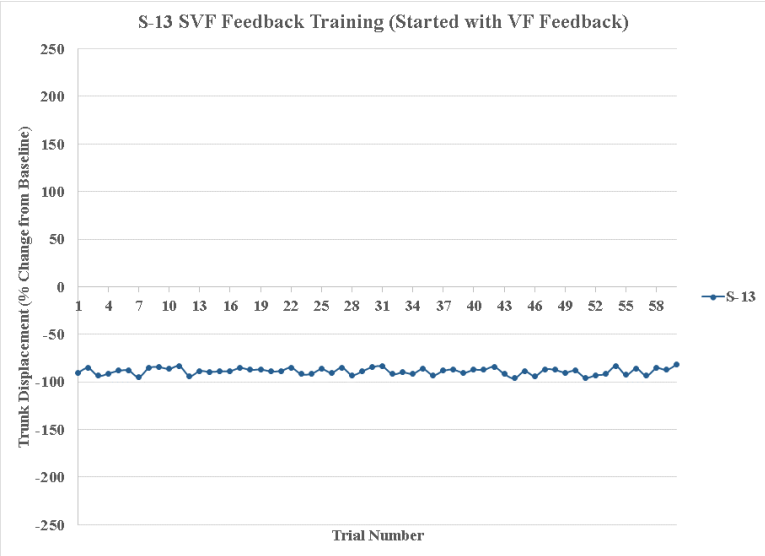

S-09 VF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-09


S-09 SVF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-09


S-11 VF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-11


S-11 SVF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-11


S-13 VF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-13


S-13 SVF Feedback Training (Started with VF Feedback)
Trunk Displacement (% Change from Baseline)
Trial Number
S-13

Appendix G End-of-Project Questionnaires

This appendix presents the end-of-project questionnaires and results. The questionnaires were administered at the end of the presentations.

G.1 Questionnaires

RIS (Reaching in Stroke)

Dissemination Questionnaire: Rehabilitation Professionals

1. **Sex:** _____ 2. **Age:** _____
2. **Type of Therapist:** Occupational Physical Other _____
3. **Experience in professional practice: Years** _____ **and months** _____

A. Presentation and Sharing of Results:

1. Attending this presentation was useful for me (circle one):

1. Strongly disagree	2. Disagree	3. Neither agree nor disagree	4. Agree	5. Strongly agree

Why (please answer)?_____

_____

_____

2. Have you ever conducted or assisted in research projects that involved human participants, excluding the one presented today (circle one)?

Yes No

3. If so, did the research teams disseminate the results from the projects to participants (circle one)?

Yes No Sometimes

4. In the future, I would like to receive more presentations about rehabilitation research findings (circle one):

1. Strongly disagree	2. Disagree	3. Neither agree nor disagree	4. Agree	5. Strongly agree

Why (please answer)?_____

_____

_____

CONTINUE IN THE BACK OF THE PAGE

B. **System Design:**

1. **If available, I would use the presented system for rehabilitating stroke survivors (circle one):**

1. Strongly disagree	2. Disagree	3. Neither agree nor disagree	4. Agree	5. Strongly agree

Why (please answer)?_____

2. **What did you like about the presented rehabilitation system (please answer)?**

3. **What did you not like about the presented rehabilitation system (please answer)?**

4. **What are the 3 most important features you are looking for in a technology-based rehabilitation system:**

1 _____

2 _____

3 _____

5. **Do you have any other comments?**

RIS (Reaching in Stroke)

Dissemination Questionnaire: Stroke Survivors

1. **Sex:** _____ 2. **Age:** _____
2. **Type of Stroke (please circle):** Haemorrhagic (Bleeding) Ischemic (Blockage)
3. **Do you suffer from weakness on one side of your body?** Yes No
4. **Time since stroke: Years** _____ **and months** _____

A. Presentation and Sharing of Results:

1. **Attending this presentation was useful for me (circle one):**

1. Strongly disagree	2. Disagree	3. Neither agree nor disagree	4. Agree	5. Strongly agree

Why (please answer)? _____

_____

_____

2. **Have you ever being a participant in a research project, excluding the one presented today (circle one)?**

   Yes No

3. **If so, have you received the results from the research projects you have participated on (circle one)?**

   Yes No Sometimes

4. **In the future, I would like to receive more presentations about rehabilitation research findings (circle one):**

1. Strongly disagree	2. Disagree	3. Neither agree nor disagree	4. Agree	5. Strongly agree

Why (please answer)? _____

_____

_____

CONTINUE IN THE BACK OF THE PAGE

B. **System Design:**

1. **If available, I would use the presented system for rehabilitation (circle one):**

1. Strongly disagree	2. Disagree	3. Neither agree nor disagree	4. Agree	5. Strongly agree

Why (please answer)?_____

2. **What did you like about the presented rehabilitation system (please answer)?**

3. **What did you not like about the presented rehabilitation system (please answer)?**

4. **What are the 3 most important features you are looking for in a rehabilitation system that uses technology (please answer):**

1 _____

2 _____

3 _____

5. **Do you have any other comments?**

G.2 Questionnaire Results

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

REDUCING COMPENSATORY MOVEMENTS IN STROKE THERAPY THROUGH THE USE OF ROBOTIC DEVICES AND AUGMENTED FEEDBACK

DISSEMINATION RESULTS

BULMARO VALDÉS
PHD CANDIDATE, BIOMEDICAL ENGINEERING
SUPERVISOR: DR. MACHIEL VAN DER LOOS

RREACH Lab
Robotics for Rehabilitation Exercise and Assessment in Collaborative Healthcare

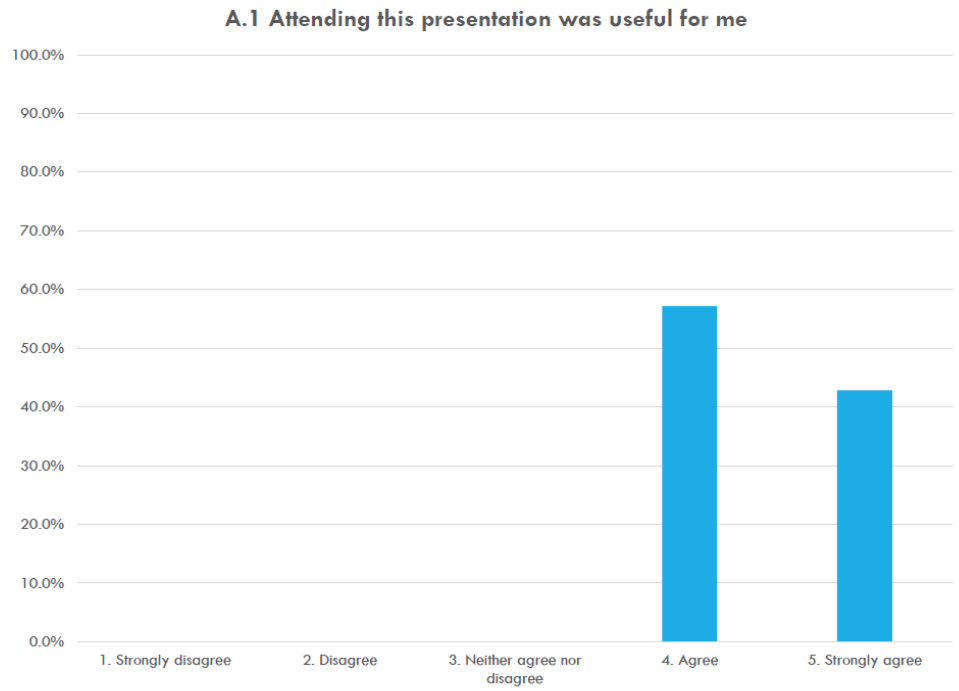
Collaborative Advanced Robotics and Intelligent Systems Laboratory

REHABILITATION PROFFESIONALS RESULTS

REHABILITATION PROFESSIONALS

	Participants	7
Gender	**Male**	0 (0%)
	Female	7 (100%)
Age (years)	**Average**	30
	SD	7
Type of Therapist	**Occupational**	2 (29%)
	Physical	2 (29%)
	Rehab Assistant	3 (42%)
Experience in professional practice (months)	**Average**	56
	SD	45

QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)



QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)

A.1.2 Why?

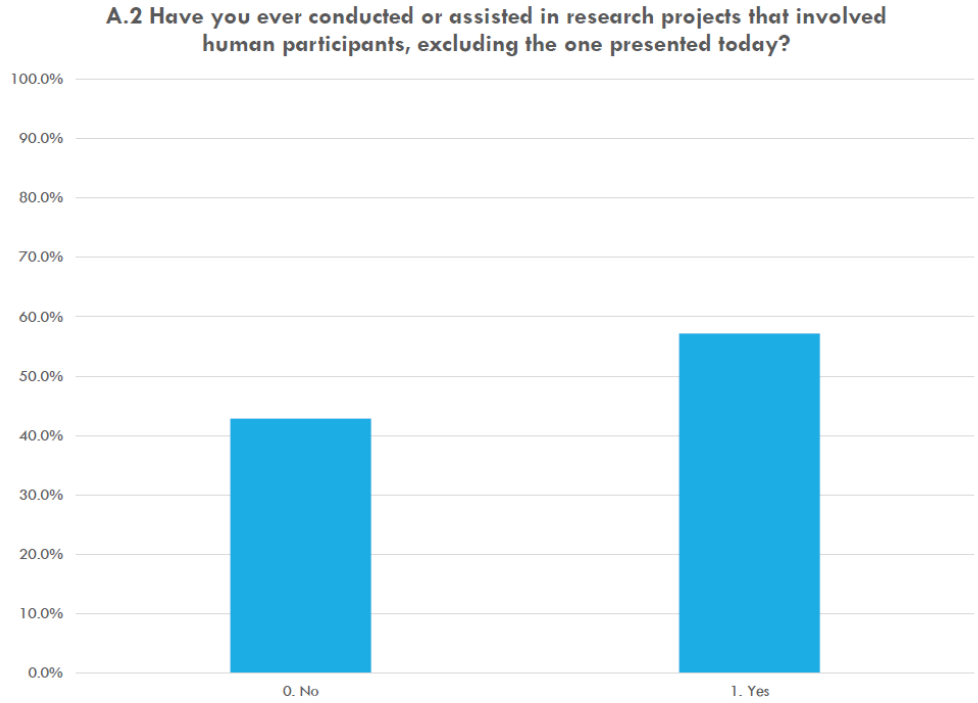
Agree:

- "Work in a clinic with stroke survivors. Compensatory patterns are a huge problem as we re-train movement of affected arm"
- "Interesting to see the effectiveness of visual/force feedback on participants' performance in reducing compensatory trunk movements"
- "At the clinic, we deal with a great deal of stroke survivors. It is interesting to see a practical application"
- "It is always interesting to hear about new innovative ways people can rehabilitate"

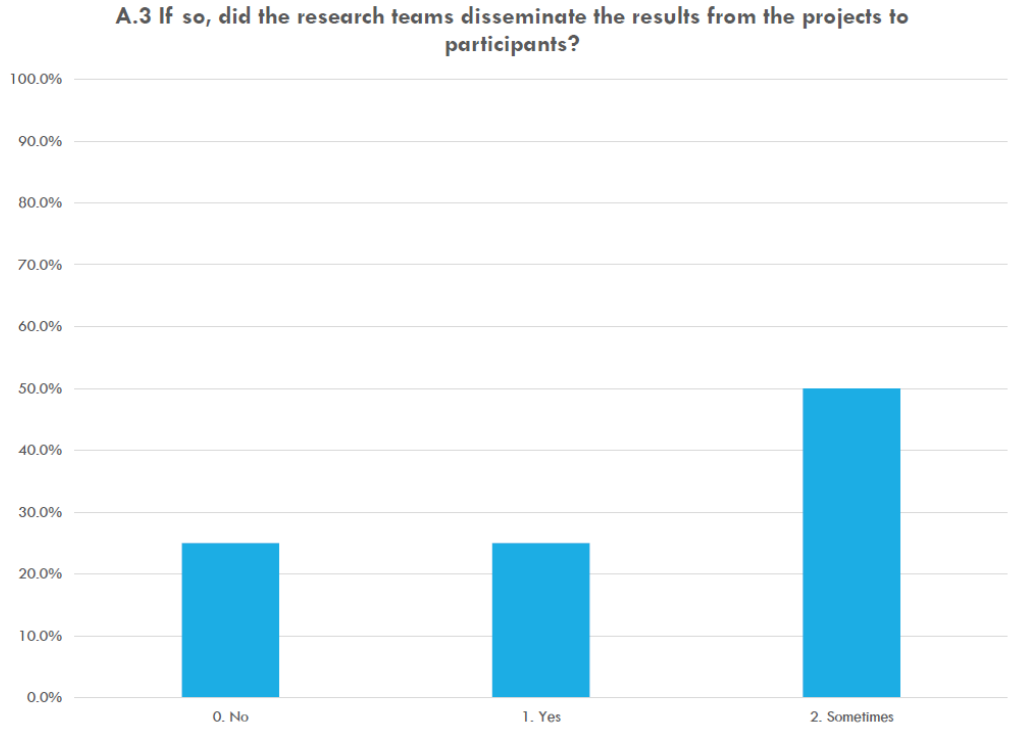
Strongly Agree:

- "As a clinician not currently involved in research I think it is very useful to see examples of current projects within the lower mainland (British Columbia, Canada)"
- "Interest and able to relate information into practice"
- "Have always seen the research on a poster at the clinic and haven't had the chance to visit the University of British Columbia"

QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)

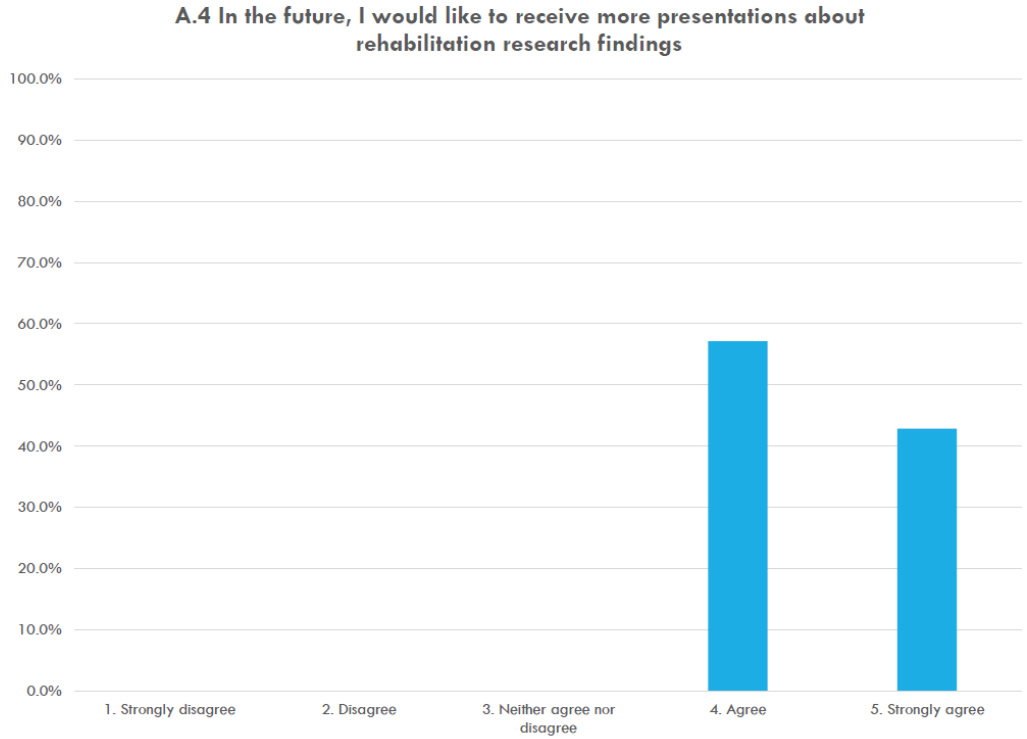


QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)



4/4 participants replied to this question after replying yes to question A.2

QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)



QUESTIONNAIRE PART A (SYSTEM DESIGN)

A.4.2 Why?

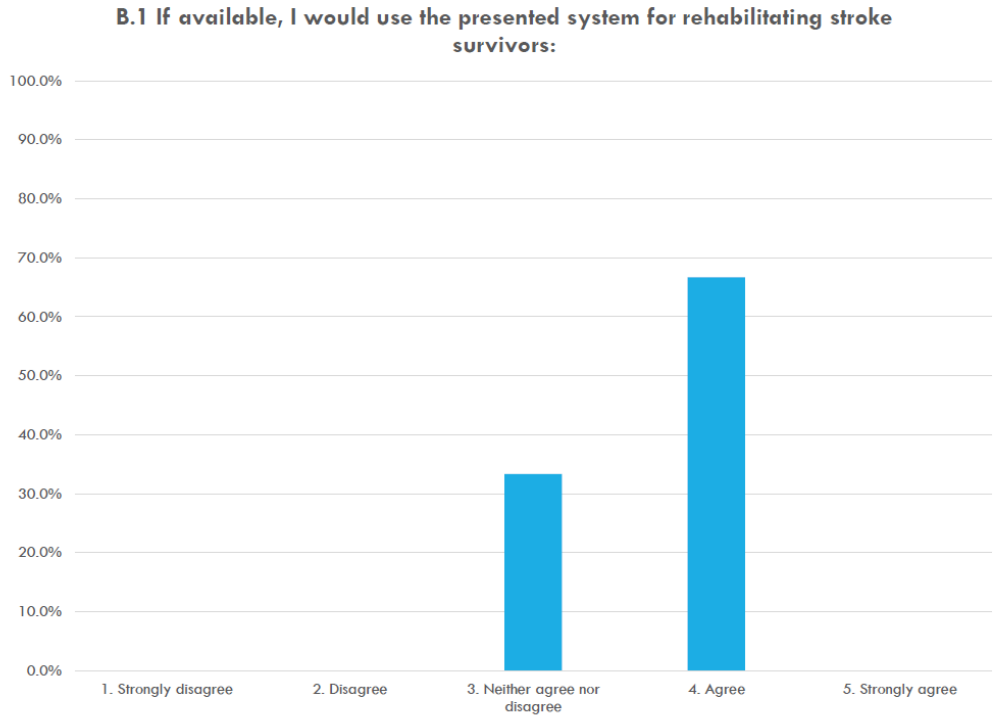
Agree:

- "Very interesting. Technology is the way of the future for rehab!"
- "Yes, it is helpful to know about current research findings"
- "It is useful to increase our own knowledge as clinicians"
- "Any education that can help people recover or adapt after a stroke is needed"

Strongly Agree:

- "It is more motivating to continue basing clinical treatments on research"
- "Gain information and understanding on different areas of rehab and its effectiveness to individualize programs"
- "Good to receive updates about current research"

QUESTIONNAIRE PART B (SYSTEM DESIGN)



6/7 participants replied

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.1.2 Why?

Agree:

- "Simple effective system. Cost limits ability to purchase it for the clinic"
- "If modified to a more exciting game"
- "Feedback for movement"
- "Innovative and fun for clients"

Neither Agree Nor Disagree:

- "Would consider using system to supplement existing therapy. Client goals may or may not be complementary to what system can offer or support"
- "It depends on the client. Time constraints of sessions could dictate whether or not it is used."

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.2 What did you like about the presented rehabilitation system

- "Simple and easy to use, and effective to support affected arm during reach"
- "Dual upper extremity task. Various feedback devices/forms. Simplicity of "game task""
- "Focus on one aspect of compensation: trunk. Simple feedback routes for participants during task: visual + resistive"
- "The application of the system in conjunction with video game technology"
- "The different types of feedback possible to individualize program and educate client on compensation"
- "Pre and post results of the study"

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.3 What did you not like about the presented rehabilitation system

- "Limited access to robot arms? Query if results may generalize to functional tasks"
- "It was great! Increasing sample size and looking at correlations between left and right lesions would be good"
- "Expense"

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.4 What are the 3 most important features you are looking for in a rehabilitation system that uses technology

1. Cost effective
2. Easy to use
3. Easy to turn on/off

1. Easy to use and setup
2. Supported by research
3. Comfortable for patients

1. Easy for client/therapist to use
2. Cost effective
3. Simple and efficient interface.

1. Practicality
2. Price
3. Durability

1. Cost effective
2. Effective results
3. Able to individualize to client

1. Feasibility for clients
2. Accessibility for clients
3. Fun for clients.

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.5 Do you have any other comments?

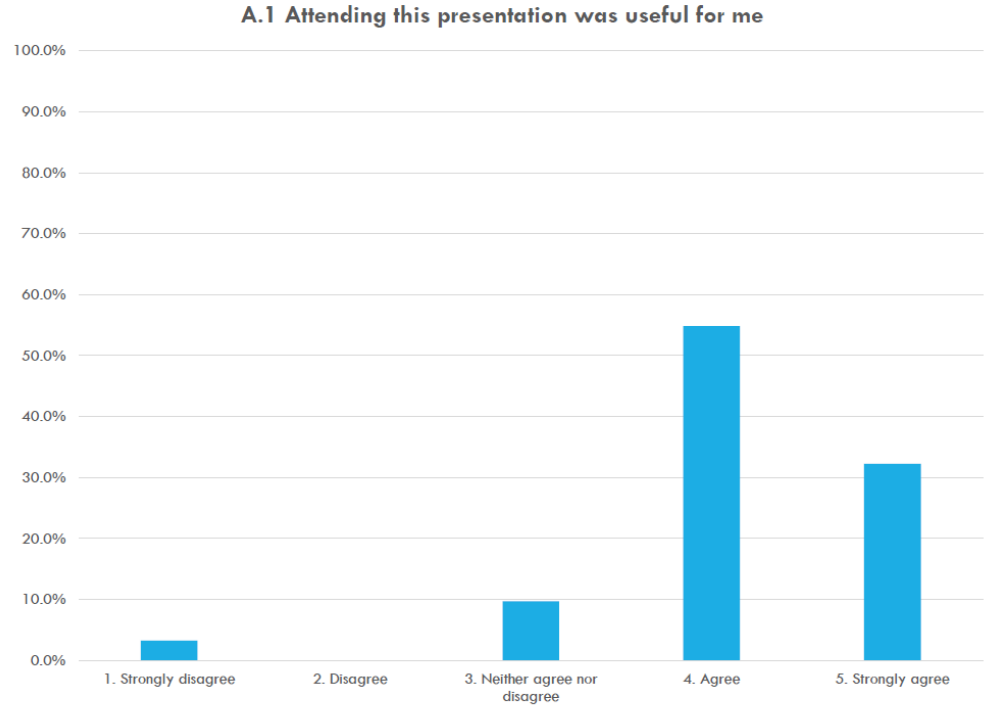
- "No. Well done! Great, clear presentation"
- "Thank you for coming out!"

STROKE SURVIVORS RESULTS

STROKE SURVIVORS

	Participants	31	
Gender	**Male**	15 (48%)	
	Female	16 (52%)	
Age (years)	**Average**	67	***30/31 participants replied**
	SD	12	
Type of Stroke	**Hemorrhagic**	8 (35%)	***23/31 participants replied**
	Ischemic	15 (65%)	
Weakness on one side of their body	**Yes**	24 (83%)	***29/31 participants replied**
	No	5 (17%)	
Time Since Stroke (months)	**Average**	85	
	SD	94	

QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)



QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)

A.1.2 Why?

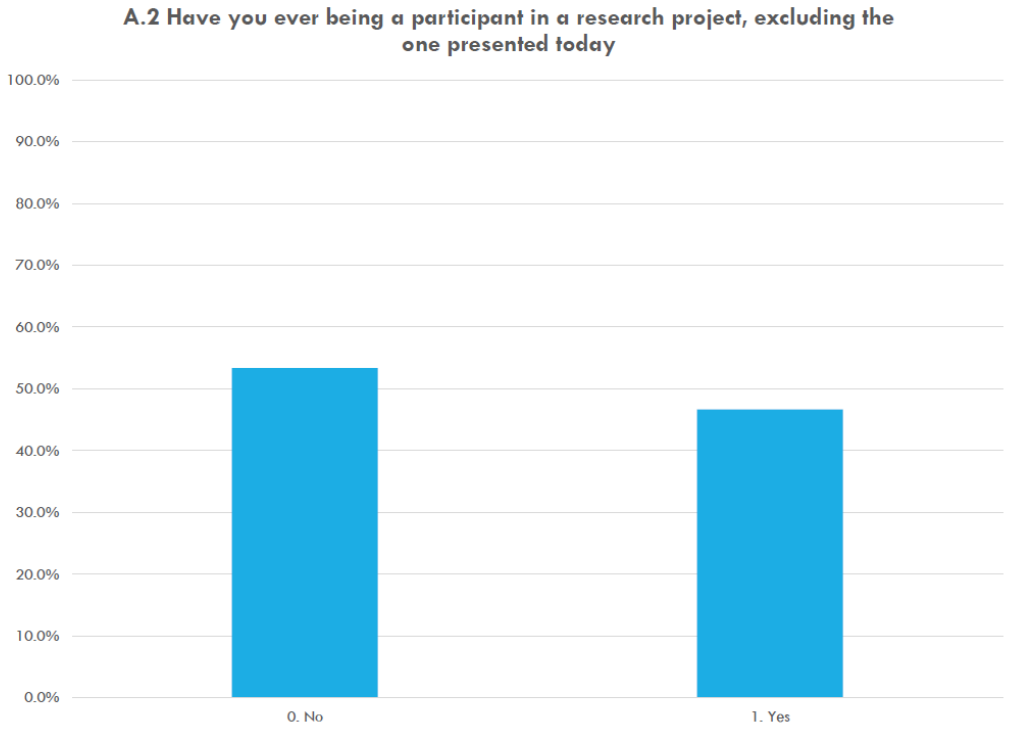
Agree:

- "Because I am interested in science, and open to new therapy ideas"
- "I learn something from these presentations, it might help me for my recovery"
- "It gives one a more interesting view on how to use your body for rehab"
- "Engaging"
- "People support, conversation, communication"
- "Because I learned so many things"
- "Learn to use my affected arm"
- "Because I was a participant"
- "Because it reinforced how important feedback is in terms of rehab"

Strongly Agree:

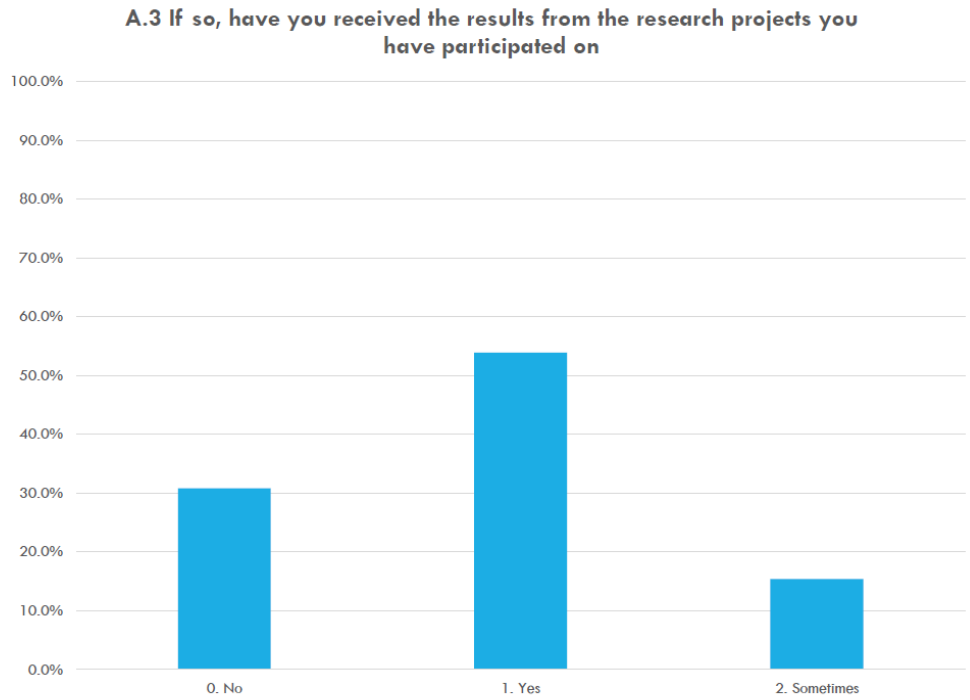
- "Very informative how the robotic features help and improve movement"
- "Reaching to a package with from back torso or lower back is painfully + wrong for ergonomics. Reaching to arms + back straight is best for everyone"
- "Seeing some results"
- "New possibilities, uplifting"
- "More information for myself and more room for self improvement"
- "Good info"
- "To know what happened in the study"

QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)



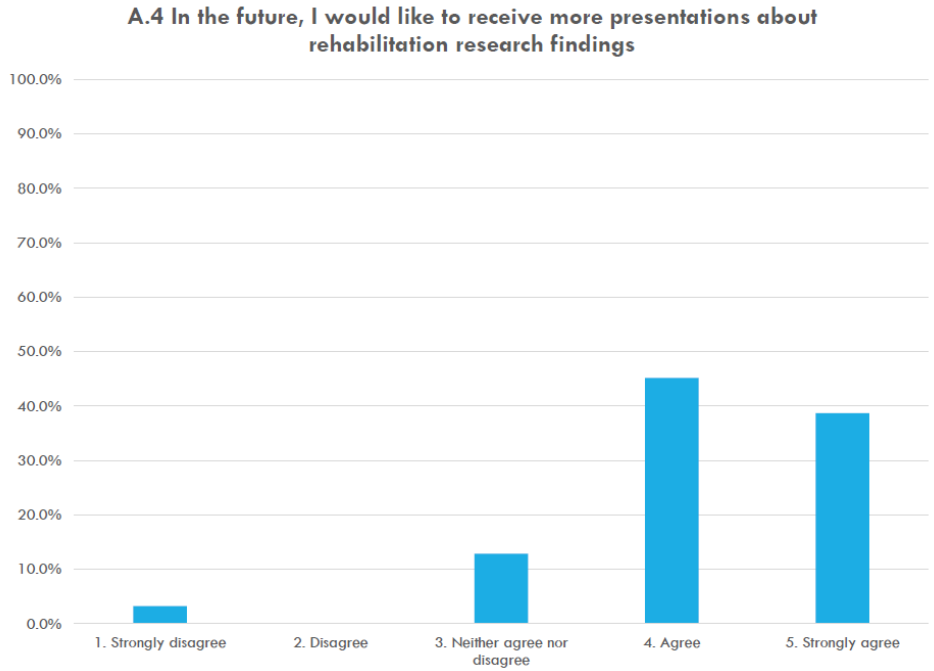
30/31 participants replied

QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)



13/14 participants replied to this question after replying yes to question A.2

QUESTIONNAIRE PART A (PRESENTATION AND SHARING OF RESULTS)



QUESTIONNAIRE PART A (SYSTEM DESIGN)

A.4.2 Why?

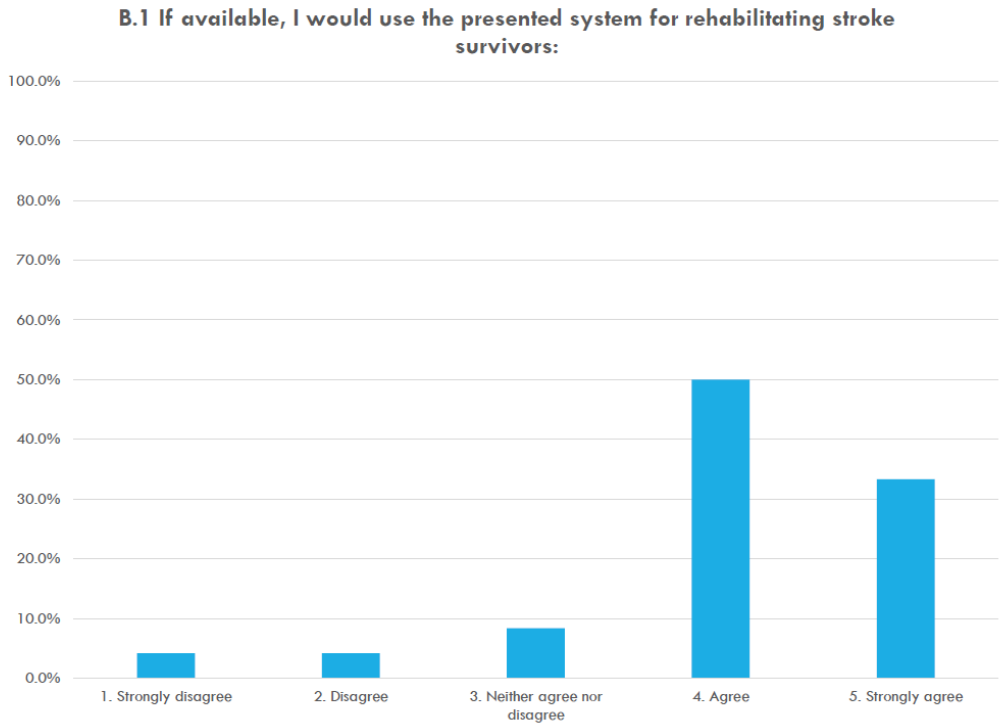
Agree:

- "Because I am interested in science, and open to new therapy ideas"
- "It could introduce me to improve my walking and balance"
- "Knowledge, may lead to less discomfort"
- "Because I want to learn and do this more"
- "Because I want to learn about the results"
- "Education is interesting"

Strongly Agree:

- "Again, just getting good information"
- "Everyone and the more research is best for everyone"
- "To get better and help others"
- "More info definitely very helpful to stroke sufferers"
- "Why not?"
- "Just for my personal information and possibly self help"
- "Just like it and keep me exercises and hope to recover"
- "Might help"
- "Because it is difficult to know about research findings about rehab studies if you don't have access to professional journals or class seminars"

QUESTIONNAIRE PART B (SYSTEM DESIGN)



24/24 participants that had weakness on one side of their body

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.1.2 Why?

Agree:

- "It would be accessible"
- "If it is beneficial"
- "Anything helps"
- "If I could afford it and if it would help"
- "To see where I am on the scale"
- "Because I saw it and liked it"
- "Might help"
- "Because it seems to have a built-in feedback loop"

Strongly Agree:

- "For progress"
- "Keep the muscles more strong"
- "To further my rehab progression"

Disagree:

- "I did not get any benefit from this trial"

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.2 What did you like about the presented rehabilitation system

- "Very good to see how you are moving the trunk without even realizing that you are doing it"
- "it's good to get results from studies even more interesting if I've been a part of it"
- "Effective"
- "Good for people with weakness"
- "Repetition of movements"
- "Fun to play with"
- "Robotics are Canadian made"
- "New possibilities"
- "Clear, precise, informative and interesting"
- "Because it works really well"
- "Givers hope"
- "Good"
- "Moving robotic arm"
- "To present the results and how improve my stroke"
- "I liked his explanation of why the things were done the way they were done"
- "The way the robotic device could provide impartial, measurable feedback"

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.3 What did you not like about the presented rehabilitation system

- "Too bulky to have at home"
- "I would like to see more videos about the study"
- "It's always difficult to get to the University of British Columbia"

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.4 What are the 3 most important features you are looking for in a rehabilitation system that uses technology

1. Video confirmation of the fact that you are moving your trunk so much
2. Giving scores for motivation to do better

1. Visual reward
2. Physically/mentally motivational
3. There is some sort of benefit for taking part: improve mentally and/or physically

1. Grasping to fingers + hands

1. That's affordable
2. Available
3. Getting guidance to do the right thing

1. Making improvement
2. No side effects
3. Tolerable

1. The accessibility of support + equipment

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.4 What are the 3 most important features you are looking for in a rehabilitation system that uses technology

1. Light weight
2. Not expensive
3. Easy to use

1. Robotic arm

1. Any possibilities to improve one's condition

1. Better balance
2. Walk better

1. Exercise
2. Movements
3. Function

1. Cost
2. Benefit to me physically
3. Not too complicated but needing some brainwork.

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.4 What are the 3 most important features you are looking for in a rehabilitation system that uses technology

1. Increase mobility
2. Non invasive
3. Light weight

1. Arm and hand

1. Available
2. Easy to use
3. Helps my hand.

1. Motion capture
2. Rewards points
3. Robotic arms and motion

1. Feedback
2. Clear presentation of what the ideal response would be
3. Something that is transferable to every day life.

QUESTIONNAIRE PART B (SYSTEM DESIGN)

B.5 Do you have any other comments?

- "I did not understand how the stick figures helped people. This was a very good presentation. I was lucky that I did not have too much problems with my movement from the stroke, but it was very informative"
- "The presenter spoke very professionally; there were no hesitations. He was very knowledgeable about the study and it's findings. He dressed nicely and was very respectful to the group"
- "Looks good for now"
- "Great program"
- "I just enjoyed it"
- "Spoken clearly. Was well prepared. Pleasant personality. Great job, great idea; we are in good hands with this new generation"
- "It was a great session with lots of information"
- "Everything you presented I enjoyed. More professional people come to talk"
- "Great idea and presentation, professional"
- "Thank you so much for the study"
- "Nice presentation and very nice to see the presenter"