Development of an Upper Limb Robotic Device for Stroke Rehabilitation

By

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A thesis submitted in conformity with the requirements for the degree of Master of Health Science
Graduate Department of Institute of Biomaterials and Biomedical Engineering
In the University of Toronto

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Abstract

Stroke is the major cause of permanent adult disability worldwide. Often stroke affects the motor control of the upper limb, leading to difficulties in performing activities of daily living. Many hours are spent in resource-intensive therapy to regain functionality of the upper limb. In order to decrease the burden to therapists and increase access to rehabilitation, an upper limb rehabilitation robotic device was developed. Observations from therapists and an international survey of stroke therapists were conducted to understand general requirements of an upper limb rehabilitation device. These requirements were the basis of the mechanical design portion of the prototype. The prototype was evaluated with stroke therapists in a focus group. Although more iterations of design, testing and evaluation are needed, this project is a step in developing a lower cost, portable device to increase access to upper limb stroke rehabilitation.
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List of Abbreviations

ADL – Activities of daily living
DoF – Degrees of Freedom
RRD – Rehabilitation robotic device
NDT – Neurodevelopmental Treatment
CIMT – Constraint induced movement therapy
RCT – Randomized controlled trial
VR – Virtual Reality
MIME – Mirror-Image Motion Enabler
ARM Guide – Assisted Rehabilitation and Measurement Guide
TWREX – Therapy Wilmington Robotic Exoskeleton
iPAM – Intelligent Pneumatic Arm Movement
DC – Direct current
POEMS – People, Objects, Environments, Messages, Services
Quanser—Quanser Consulting, Inc. (Markham, ON, Canada)
TRI – Toronto Rehabilitation Institute
OT – Occupational therapist
PT – Physiotherapist/Physical Therapist
SLP – Speech and Language Pathologist
EMG – Electromyographic/Electromyography
MVC – Maximum voluntary contraction
ROM – Range of motion
+ve – Positive
-ve – Negative
Ref – Reference
AC – Alternating current
DC – Direct current
FFT – Fast Fourier Transform
3D – Three dimensional
2D- Two dimensional
COM – Centre of mass
List of Symbols

Equation variables:
F – force
m – mass
a - acceleration
P – power
I – current
V – voltage
T – temperature
f – frontal axis workspace
s – sagittal axis workspace
l – longitudinal axis workspace
n – sample size
z – standard deviation units
p – estimate of variance
d – confidence interval
X – finite discrete random variable
μ – coefficient of friction
τ – torque
r – link length
μX – mean of X
dX – width of X
O – observed
E – expected
Rf – cooling rate
P – radius of gyration

Measurements:
Kg – kilogram
mm – millimeter
cm – centimeter
V – volts
W – watts
LFM – linear feet per minute
CFM – cubic feet per minute
°C – degrees Celsius
Chapter 1. Introduction

This chapter will introduce the need for upper limb stroke rehabilitation and give one possible solution with rehabilitation robotics. In addition, it will introduce the research objectives, questions, scope, organization of the paper, and related publications.

1.1 Problem statement

1.1.1 The burden of stroke

Every year stroke affects 16.3 million people worldwide. It is the second leading cause of death and the leading cause of permanent disability in adults [1]. The worldwide burden of stroke is increasing and expected to rise to 23 million first-ever strokes by 2030 [2]. Among those who have experienced a stroke, there are an estimated 64.5 million stroke survivors who live with varying levels of disability and need assistance for activities of daily living (ADL) [1]. The burden of care for stroke survivors is high for the healthcare system and family members or caregivers [1], [3].

Many hours are spent on post-stroke rehabilitation to improve function, reduce impairment, and enable stroke survivors to live more independently. A great part of stroke rehabilitation involves improving motor function. Approximately 80% of stroke survivors have motor deficits, which can result in serious disability [4]. Often the upper limbs have more severe impairments as the brain artery responsible for blood flow to areas which control the upper limb is frequently involved in a stroke [5]. Therefore it is important for the upper limb to be supported and rehabilitated to perform ADLs, such as eating, bathing, and dressing.

Timely access to stroke rehabilitation is crucial for maximum stroke recovery [3]. There are several factors that may result in inadequate access to stroke rehabilitation. These may include an uneven distribution of resources, inadequate insurance coverage, or a lack of knowledge of the potential value of rehabilitation [6]. An uneven distribution of resources may
be due to location, for example those in remote locations may have less access to trained therapists. Within Canada, for example, stroke rehabilitation services are seen to be inadequate due to insufficient facilities, funding, and staff [7]. Staff may be limited due to a shortage of qualified stroke therapists. This situation may be further exacerbated in the future, especially in areas where there is an aging population and a diminishing workforce. These issues may limit a stroke survivor’s therapy in terms of frequency and duration.

1.1.2 Rehabilitation robotics – a possible solution?

Hillman defines rehabilitation robotics as the application of robotic technology to the rehabilitative needs of people with disabilities as well as the growing elderly population [8]. Rehabilitation robots have been developed to alleviate the burden on therapists and healthcare systems, while simultaneously increasing access to rehabilitation. Several studies have shown similar improvement in stroke survivor outcomes with the use of rehabilitation robotic devices (RRD) when compared with conventional therapy [9-11]. Clinical acceptance of a robotic rehabilitation device may also be related to robotic capabilities that would be difficult to achieve with conventional therapy [12], [13]. Features such as exact repetitive movements, programmable resistance, objective evaluation, and movement sensing capabilities would theoretically increase clinical acceptance. Although robots will likely never replace therapists, they may be useful in aiding therapists or extending rehabilitation to remote locations or to the home.

1.2 User centered design

In order to design future RRDs it is imperative to obtain an understanding of what therapists and their clients would use and why the currently available devices are not commonly used. Designing a usable RRD must address the needs of its end users; therefore, end users must be consulted. Human factors research has shown that the development of a usable system requires the end users’ input throughout the design process. User-centered design is a technique that focuses on the users’ needs and designs according to these needs
In the development of rehabilitation technology, it is especially important to have the input and expertise of many individuals. It is the proposal of this thesis to use a user-centered design process to create an upper limb RRD for stroke survivors and their therapists.

User-centered design is an iterative design process, which incorporates the following key principles (adapted from [17]):

- Work practices of the user control the development.
- Representatives from end user groups should be actively involved early and continuously throughout development.
- The development should undergo many iterative cycles to come up with requirements from the end users.
- Prototypes should be created early and continuously to visualize and evaluate ideas.
- The development process should be performed by interdisciplinary teams.

1.3 Past work

A preliminary prototype of a haptic robotic platform for upper-limb reaching stroke therapy had been previously designed by the researcher’s lab and later evaluated by clinicians. While the overall impressions of the clinicians were favorable, several aspects of the device have been identified as requiring redesign, including the support structure, and the end effector. Other aspects of redesign would be discovered using user-centered design principles.

1.4 Objectives

The objectives of this research are to:

1. Determine what factors contribute to designing a usable, cost effective upper limb RRD for stroke survivors and stroke therapists;
2. Design and construct a prototype device aimed at upper-limb rehabilitation based on information from objective one;
3. Evaluate the resulting prototype device with a focus group of therapists, and
4. Evaluate the maximum range of motion and force through an initial biomechanical analysis.

1.5 Research questions

This study will attempt to answer the following questions:

1. What role can rehabilitation robotics play in upper limb stroke therapy?
2. What form of robotic technology would aid clinicians in upper limb stroke therapy?
3. What would be the design specifications of a low-cost, usable RRD?

1.6 Scope of research

The primary focus of this research is to create specifications for a hardware design of the mechanical portion of an upper limb RRD, and to evaluate the resulting prototype with respect to safety and usability. This does not include the computer-user interface, firmware, software, or games/activities the system would eventually have.

1.7 Organization of thesis

Chapter 2 gives background on stroke and stroke rehabilitation. Chapter 3 reviews upper limb robotic rehabilitation devices in the literature. Chapter 4 describes observations of therapists in their workplace. Chapter 5 gives a description of an international survey of therapists. Chapter 6 explains the preliminary design using the House of Quality. Chapter 7 describes the potential risks the prototype. Chapter 8 presents the evaluation and discussion from a focus group of therapists. Chapter 9 evaluates the biomechanics of the arm while using the device. Finally, Chapter 10 evaluates the development process for the device, gives final conclusions, and discusses future work.
Chapter 2. Background

This chapter gives an overview of stroke and stroke rehabilitation as the scientific basis for neurorehabilitation.

2.1 Stroke and motor impairment

Stroke (a cerebrovascular accident) occurs when there is an interruption of the blood supply to the brain. As blood is the carrier of nutrients to cells in the brain, a stroke occurs when cells are unable to maintain normal ion gradients due to a lack of oxygen. This in turn leads to cell death [19]. Loss of blood can occur in two main ways – through a hemorrhagic stroke, where the blood vessels rupture and blood loss occurs; or through an ischemic stroke, where there is blockage to the normal flow of blood to the brain, from a narrowed artery or from a blood clot that has broken off from another place [20].

Unlike many other cells in the body, neurological cells, including brain cells, lose the ability to reproduce after early development [21]. The cells affected by a stroke lose their functionality when they die. For example, if the cells that aid in speech production die, speech would be affected or if the cells aid involved in movement production die, movement would be affected. Consequently each stroke survivor has specific impairments that are related to specific brain cells which have died. In addition, every person has a unique pattern of brain organization which would affect different impairment levels when brain cells die.

When the motor cortex, premotor cortex, motor tracts, or associated pathways in the cerebrum or cerebellum are affected by stroke, the effect is motor impairment, which typically affects movement of the face, arm, and leg of one side of the body [4]. Motor impairment can have the effect of limiting a person’s ability to perform ADLs, which would affect their ability to participate in society and remain independent [3],[4].

2.2 Stroke recovery

There are at least three factors underlying stroke recovery: resolution of acute tissue damage, behavioral compensation, and brain plasticity [22]. Much of the initial stage of
spontaneous recovery is due to a decrease in edema, hemorrhaging, and inflammation. Behavioral compensation occurs as stroke survivors develop compensational strategies to deal with their impairments. The third factor, brain plasticity, is the underlying basis for stroke rehabilitation.

After a cerebrovascular accident, the brain is able to regain its lost functionality through reallocating cell function. This is due to two factors: the brain having diffuse and redundant connections and its ability to form new structural and functional circuits through remapping [19]. Research shows that there is not just one neurological pathway for a certain function, but also many redundant pathways. For example, although contralateral pathways (i.e. one hemisphere of the brain controlling the opposite side of the body) are generally dominant, ipsilateral pathways (i.e. one hemisphere of the brain controlling the same side of the body), are also present. These redundant pathways can be strengthened over time [19].

The brain is more plastic after a stroke. Although cells do not reproduce, they are able to remodel, or change their structure and functionality with input from the environment [23]. The cells physically closest to those which have been affected by stroke (the peri-infarct cortex) are the ones that actively remodel after a stroke. It has been shown that immediately after a stroke, this region is able to sprout new axons, creating new connections [22]. Remodeling of the lesioned brain is activity driven and affected by the environment [24]. This remodeling activity is extremely time-dependent and activity-dependent [19]. Competing activities vie for the peri-infarct cortex cell function, so it is imperative for these cells to form connections to regain function that was lost during the stroke [19]. Activity of the affected limbs immediately following stroke is therefore vital to limb functionality.

There are two main mechanisms for brain plasticity – homeostatic and Hebbian plasticity. Homeostatic plasticity occurs as the body seeks to restore homeostasis after the synaptic activity disruption during a stroke. The surviving neurons undergo increased excitability that may contribute to more neuron connections immediately after a stroke. Hebbian learning occurs when both presynaptic and postsynaptic neurons are active at the same time, strengthening their connection [25]. Lindberg et al. has been found that specific forms of use-
dependent training, even passive movement can influence cortical remapping [26]. As an example, constraint-induced movement therapy (CIMT) blocks activity of the unaffected arm and results in increased plastic changes in the brain for the affected arm [27]. CIMT counters the learned non use many stroke survivors have of their paretic limb. In addition, mental practice may be another way to coincident cell activity, thereby strengthening cell connections to motor pathways [28]. Hence, repetitive activities that strengthen motor neural pathways aid in the recovery of the corresponding limbs for the stroke survivor.

Just as there are critical time periods for early development of the brain, so there are critical periods for rehabilitation immediately after a stroke. Rats which were exposed to enriched rehabilitation at different periods after a middle cerebral artery stroke showed those with early rehabilitation had significantly better recovery than those with delayed treatment [29]. This critical period has also been shown in humans, and it has been shown that early rehabilitation and more aggressive rehabilitation has resulted in higher functional scores [30]. However, after the critical time period for recovery, the brain is still able to remodel and motor functions are able to recover, although at a slower rate [19]. Therefore access to rehabilitation is crucial, especially during the early phases of stroke recovery.

2.3 Implications for rehabilitation robotics

RRDs may be able to increase access to rehabilitation, especially during the crucial period immediately after a stroke. For some stroke survivors, this may mean the difference between partial and full recovery of motor function. Outcomes of the affected limb are often dependent on its activity. As many stroke survivors would prefer to use their unaffected limb, the disuse of their affected limb can be detrimental to recovery.

Rehabilitation robots are able to offer an enriched environment even for minimally functioning limbs. Stroke survivors who have minimal usage of their affected limbs often are unable to participate in therapies such as CIMT. The more enriched the environment, the more senses involved, and the stronger the Hebbian pathways. Robotic devices are able to repetitively move the arm, giving the brain sensory input over and over again. If there are other cues, which could be provided in a virtual reality environment, these could also
strengthen neurological pathways for motor recovery. Just as mental imagery aids in strengthening the neural connections, imaging through a virtual environment does the same [31]. The advantage that a robot has is it can combine a highly repeatable task (moving the limb) with feedback about performance, which provides the motivation to practice more. Repeated practice needs to have feedback of incremental success to give people motivation to continue [31]. Virtual environments can do that in a way real environments cannot, in the form of feedback and motivating activities and games. Virtual environments combined with a rehabilitation robot can provide repetitive movement, informative feedback, and motivating activities.
Chapter 3. Literature Review

In order to better understand the features of current upper limb robotic rehabilitation devices, a literature search was done on Compendex, Google Scholar, and Medline. The search terms that limited articles concerning stroke were: “cerebrovascular accident”, “cerebrovascular disease”, and “stroke”. The search was then narrowed to articles containing “upper limb”, “upper extremity” or “arm”. Finally the search was narrowed again to articles containing “robotic rehabilitation”. Abstracts of the narrowed search were then reviewed and further narrowed down, taking special interest to those devices that have been clinically tested and those working with the proximal upper limb. In all 80 documents were initially reviewed. Other articles (13) were reviewed as they came to the researcher’s attention. The upper-limb robotic devices described below do not include all the upper-limb rehabilitation robots in the literature. Thirteen devices were chosen based on devices which have been clinically tested, those working on the proximal upper limb, and those which are on the market.

3.1 MIT-MANUS/InMotion2

3.1.1 Description

The most clinically studied upper limb robotic rehabilitation device is the MIT-MANUS, or its commercial version, InMotion2 (Interactive Motion Technologies, Cambridge, MA). This robot has two degrees of freedom (DoF) and is an end-effector type of robot. The user’s paretic forearm is placed in a supporting trough, which is then attached to an end-effector. The user moves the handle in the transverse plane, performing goal-directed tasks which focus on shoulder and elbow movement. A monitor displays user targets and provides visual feedback, as shown in Figure 3-1. The MIT-MANUS has developed over the years to include modular components that allow a one DoF vertical movement and a three DoF wrist movement [32], [33], as well as a grasp sensor [34]. The MIT-MANUS has three modes for the user: resisted, where the robot gives the user resistance in the opposite direction the user is moving; active, where the robot magnifies the user’s actions in the direction the user is moving; and assisted movement, where the robot does all the moving and the paretic arm is
passively moved. The MIT-MANUS is able to generate more or less assistance depending on the user’s ability [35]. The two DoF horizontal robot is portable (390 N) and has a backdrivable five bar-linkage SCARA (selective compliance assembly robot arm) mechanism, which is impedance controlled [33]. The MIT-MANUS as an end-effector system only allows for movement detected at the hand. Horizontally, it has two DoF and vertically it has a separate one DoF.

![Image](image_url)

**Figure 3-1. The InMotion2 (MIT-MANUS)** © Interactive Motion Technologies, used with permission [30].

### 3.1.2 Clinical outcomes

Clinical results from the MIT-MANUS and InMotion2 robotic rehabilitation devices have been promising. Many random controlled trials (RCT) have shown statistically significant decreases in impairment for the shoulder and elbow from the start of robotic therapy to the end of the study, although statistically significant increases in functional performance have not been shown [36-40]. These decreases in impairment have been shown for acute, sub-acute, and chronic stroke survivors. The sample sizes of the studies have ranged from 20 to 127. Robotic therapy with the MIT-MANUS has also shown comparable increases as compared to group therapy and intensive traditional therapy [41], [42]. One large multi-centre RCT study found that the MIT-MANUS did not significantly improve outcomes after 12 weeks when
compared to usual and intensive therapy, but did significantly improve outcomes after a three month follow-up when compared to usual therapy, but not compared to intensive therapy [9].

3.2 MIME

3.2.1 Description

The Mirror-Image Motion Enabler (MIME) is based on the principle of bilateral movement, where stroke recovery is affected by corticospinal ipsilateral pathways. These pathways are active in healthy bilateral movement. The hypothesis is that bilateral symmetrical exercise will stimulate these pathways and assist in stroke recovery [43]. The MIME consists of a six DoF end effector for the paretic arm, which has actuators to apply forces in goal-directed movements. The arm is strapped to the end effector, which restricts wrist and hand movement. A PUMA 560 robot (Staubli Unimation Inc., www.staubli.com) is attached to the splint. The less affected arm is strapped in a similar splint, but not attached to the robot (See Figure 3-2). The MIME has four modes: passive mode, where the robot moves the relaxed limb; active-assisted mode, where the user triggers an action and the robot produces forces in the same direction to magnify user movement; active-constrained mode, where the robot produces forces in the opposite direction of user movement to provide resistance; and bilateral mode, where the less affected arm moves and the robot moves the affected arm, in a mirror-image symmetrical way [44].
Figure 3-2. The MIME rehabilitation robotic device a) unilateral mode, and b) bilateral mode © Peter Lum, used with permission [45].

3.2.2 Clinical outcomes

In two RCTs, the MIME has shown to improve impairment and muscle activation for subacute and chronic stroke survivors [44], [45]. There were 27 chronic subjects in one study and 30 subacute subjects in the other. One study showed statistically significant improvement for the MIME group compared to a control group which had conventional neurodevelopment
treatment (NDT). However seven months after the study these differences faded [44]. Of special note, when the unilateral mode was tested against the bilateral mode, it was found that the unilateral and combined (unilateral & bilateral) modes showed significant improvement over the control (NDT) and the bilateral mode [45].

### 3.3 GENTLE/s

#### 3.3.1 Description

The GENTLE/s uses a commercial haptic robot (HapticMaster, Moog Inc., www.moog.com), with a virtual reality (VR) display to motivate users to engage in therapy. The GENTLE/s is an admittance controlled RRD. Along with the robot and the VR display, the system includes a chair, shoulder supports, a wrist connector, an elbow orthosis, two computers, a large monitor with speakers, an exercise table, and a keypad. The arm is suspended to overcome the negative effects of gravity on the paretic arm and to help with shoulder subluxation (See Figure 3-3). The VR simulates three environments: an empty room, a real room with some general shapes, and a detailed room with several objects [46].

The GENTLE/s system uses a minimum jerk polynomial pathway to calculate the robotic movements, allowing a straight line path that has zero acceleration at the start and end of the path. There are three modes: the passive mode, where the passive arm is moved by the robot; the patient active assist mode, where the user initiates movement and the robot assists in the same direction, and patient active mode, where the user moves the device. In the patient active mode if there are deviations from the predefined path, the robot creates resistance to allow the user to return to the pathway [46].
3.3.2 Clinical outcomes

Coote et al. conducted a study of 20 chronic stroke survivors with the GENTLE/s system and the arm in a sling in an ABC and ACB type study (A = baseline, B = rehabilitation with the GENTLE/s system, C = rehabilitation with arm in sling). This study showed that people using the system had a higher rate of recovery during the rehabilitation robotic phase compared to the arm in sling phase or during the baseline phase [47].

3.4 ARM Guide

3.4.1 Description

The Assisted Rehabilitation and Measurement Guide (ARM) was designed to assess multi-joint coordination and the workspace deficits of a paretic arm in a quantitative manner. This would eventually allow the quantitative assessment of tone, spasticity, and coordination [48]. The ARM Guide attaches to the user’s forearm with a custom splint and guides the arm on a linear path, measuring range of motion (ROM) and constraint forces (See Figure 3-4). It is balanced so that the user doesn’t experience any static loading from the ARM Guide [49]. The
second goal of the ARM Guide was to be able to therapeutically treat a paretic arm through repetitive movement.

Figure 3-4. The ARM Guide
© David Reinkensmeyer, used with permission [48].

3.4.2 Clinical outcomes

Initial testing has shown that the ARM Guide is able to detect workplace deficits, although it may not accurately measure the constraint forces due to a mismatch in geometry of the ARM Guide and normal reaching movements [49]. In a pilot study, three chronic stroke survivors were trained on the ARM guide in active assist mode (where the robot provides forces in the same direction as the user). In this limited study, two out of the three subjects improved in ROM (the third subject had full ROM from the onset) and tone. There was lack of improvement in coordination and free reaching movement for one of the subjects [48]. Kahn conducted a RCT which found no significant difference between chronic stroke survivors using the ARM Guide and those who did reaching exercises [50].

3.5 T-WREX (ArmeoSpring)

The Therapy Wilmington Robotic Exoskeleton (T-WREX), or its commercialized version – the ArmeoSpring (Hocoma AG, www.hocoma.com) is a passive five DoF arm-orthosis designed to support those with arm weakness in intensive movement training by reducing the effects of gravity (See Figure 3.5). The T-WREX uses rubber bands to provide various levels of arm support and has position sensors at each joint, which can measure arm movement. It is able to
be used in conjunction with a computer to allow the user to interact in a VR environment and play games [51].

![Figure 3-5. The ArmeoSpring passive arm orthosis](image)

© Hocoma AG, photo courtesy of Hocoma AG, used with permission.

### 3.5.1 Clinical outcomes

Clinical tests on chronic stroke survivors have shown that it is comparable to conventional weight-bearing exercise in decreasing impairment and increase in use of the paretic arm. A study of 23 subjects compared the T-WREX to conventional self-directed exercises. Although the T-WREX subjects had gains in arm movement mobility, it was not found to be significantly higher than the control group [51]. Another RCT of 28 subjects found that T-WREX subjects had comparable improvements to tabletop support subjects in impairment; however, the T-WREX group had significantly better impairment scores six months post-treatment. Qualitatively, subjects favored the T-WREX over conventional exercise [52].

### 3.6 Bi-Manu-Track arm trainer

#### 3.6.1 Description

The Bi-Manu-Track works under the principle of bilateral training; however it works on the area of the forearm and the wrist. The Bi-Manu-Track allows one DoF for pronation/supination
of the forearm, and when used upright, one DoF for dorsiflexion/volarflexion of the wrist. It is a portable, lower-cost system with two motors with torques of up to five Nm [53]. The device is connected to a computer which collects data and controls the motors. A visual display shows the number of cycles performed. The robot has adjustable impedance control with force and position registration. There are three modes for the Bi-Manu-Track: passive mode, where the robot moves both arms; active-passive mode where the less affected arm moves the affected arm in a mirror-like fashion; and active-active, where both arms initiate movement (the paretic arm has to overcome a threshold resistance) [54].

3.6.2 Clinical outcomes

When tested with chronic stroke survivors, the Bi-Manu-Track improved motor functions in five out of twelve subjects, and improved muscle tone in eight out of twelve. However, the improved motor functions did not translate into better functional performance in ADLs [54]. The study did not have a control group and the subjects were also concurrently involved in a comprehensive rehabilitation program [54]. A RCT study done on the Bi-Manu-Track with 44 subacute stroke subjects had one group used the Bi-Manu-Track, while the other group used electric stimulation therapy (both groups were also participating in conventional therapy at the same time). It was shown that the impairment scores improved for both groups. However, they improved significantly more with the Bi-Manu-Track; six months post treatment, there was no difference between the groups [55].

3.7 Reha-Slide

3.7.1 Description

Like the Bi-Manu-Track, the Reha-Slide works under the principle of a lower cost bilateral arm trainer. The Reha-Slide allows for three degrees of freedom at the shoulder, elbow, and wrist. It is meant to be a lower cost passive system which allows the unaffected arm to aid the affected arm. The two handles are connected by a rod and mounted on two sledges. The user can move the handles back and forth (30 cm) and sideways (15 cm) and the rod can rotate. A
computer monitor gives visual feedback to the user who is able to exercise with motivational games [56].

### 3.7.2 Clinical outcomes

A RCT of 54 subacute stroke survivors underwent therapy with the Reha-Slide or electrical stimulation over a six week period in addition to standard care. Both groups improved significantly over time. There was no statistical significance between the two groups for the primary outcome variable for arm impairment (Fugl-Meyer Assessment Scale). However, significantly more stroke survivors were able to transfer more blocks in the Reha-Slide group compared to the electrical stimulation group, although statistically significant differences were not found after a three month follow-up [56].

### 3.8 REHAROB

#### 3.8.1 Description

![Figure 3-6. The REHAROB system](image)

© Gabor Fazekas, used with permission [57].

The REHAROB uses unmodified industrial robots to perform passive physiotherapy at a constant velocity (see Figure 3-6). The REHAROB consists of two robotic devices which connect
to the hemiparetic arm in an exoskeleton type fashion. The user controls an enabling device to turn on the robots. These robots are “trained” by therapists, who go through the motions of an exercise and then edit them on a computer. The robot is then able to duplicate the exercise on another person. To ensure safety for the user, the robot must be activated through pushing an enabling device, held in the less affected arm of the user.

3.8.2 Clinical outcomes

There have been few clinical trials on the REHAROB. In usability testing, it was found that constantly pressing the enabling device was found to be tiring for users [58], the safety mechanism would accidently go off and the robots resistance to the “training” phase was high [57]. The subjects (four healthy and eight hemiparetic) in one study received traditional therapy alongside robotic therapy. These subjects had an increase in functionality and a decrease in spasticity [57].

3.9 ARMin (ArmeoPower)

3.9.1 Description

The ARMin and ARMin II or the ArmeoPower (Hocoma AG) are six DoF exoskeleton robots with haptic displays (see Figure 3-7). They have position, force, and torque sensors and are driven by cables and backdrivable impedance controlled electric motors. The ARMin has four actuated and two passive DoF. The exoskeleton is mounted on a mobile platform and can be adjusted to different sized arms. The ARMin has gravity compensation and is connected to a computer which gives audiovisual (3D) and haptic feedback, allowing users to practice ADLs. The device has two modes, one where the user is passive (mobilization mode) and another where the robot waits for the user to initiate activity (game supported therapy). During mobilization mode, therapists must record a normal arm trajectory for the ARMin, which is then processed to generate a smooth arm movement. The robot uses user-driven trajectories and corrects trajectories only when they interfere with task performance. The ARMin has safety features such as mechanical stops for joints and smooth edges as well as redundant position sensors, current and speed monitoring, software watchdog systems, and a dead-man
switch for the supervising therapist. When something abnormal happens, the safety circuit cuts power to the motors [59]. The ARMin II has been extended to include six actuated DoF and one coupled DoF so as to include rehabilitation of both proximal and distal joints [60].

![Image of ARMin II](image)

**Figure 3-7. The Armeo Power actuated rehabilitation robot**  
© Hocoma AG, photo courtesy of Hocoma AG, used with permission.

### 3.9.2 Clinical outcomes

In a usability pilot study with healthy subjects, eight hemiplegic stroke subjects, and three spinal cord injury subjects, it was found the subjects were able to perform movement tasks and were generally positive toward the ARMin. However, there were some problems with the fixation of the device (which took an average of five minutes) and those with unstable shoulder joints could not be treated by the robot. The ARMin II addresses this problem by moving the shoulder in anatomically correct positions [55]. In a pilot study, four chronic stroke survivors received therapy from the ARMin II. Three out of four subjects had significant improvements in their Fugl-Meyer assessment scale score of the upper extremity, most of which were maintained after a six month follow-up. However, the subjects were not able to translate gains in motor function to activities of daily living [60].
3.10 Braccio di Ferro

3.10.1 Description

The Braccio di Ferro is a backdrivable haptic end-effector system with two DoF, which uses impedance control to direct two motors (see Figure 3-8). It has a large elliptical workspace (80cm x 40 cm). The Braccio di Ferro is able to generate large forces (50 N of continuous force and 200 N of peak transient force). The device comes as a workstation, which is able to adjust to different planes of motion [61]. The user grasps an end-effector and the forearm is supported by a low-friction sliding device which allows movement in the horizontal plane. The user sits in front of a monitor which gives a visual display. Users perform reaching motions with a robot-activated force field, which can aid the user depending on how much force is being applied by the user. The force field and the visual cues are to reinforce proprioception. The haptics included an assistive force field, a viscous drag to dampen hand oscillations, and a virtual wall.

3.10.2 Clinical outcomes

A pilot study was conducted with ten chronic stroke survivors who were undergoing NDT therapy. The study had subjects undergo open-eye trials and closed-eye trials to induce subjects to focus on proprioceptive feedback. Results from this study showed that overall subjects had decreased impairment scores and decreased levels of assistance. It also showed that for most subjects there was little difference between the vision and no-vision modes [62].
3.11 iPAM

3.11.1 Description

The Intelligent Pneumatic Arm Movement (iPAM) is an exoskeleton robotic system which consists of two pneumatically actuated arms, which have three DoF each (see Figure 3-9). The robot is gravity compensated, so that the user’s limb is unloaded in a pressure-cuff. The two motors are coordinated through a kinematic model of the arm and use a Cartesian admittance scheme so that the arm is not loaded in unnatural ways. There are three different modes: the gravity compensation mode, where the robot compensates for its own weight, but does not actively assist the user; a hand trajectory mode, which acts like an end-effector robot, (the upper robot acts in gravity compensation and the lower robot operates on admittance control); and a joint control mode, where both robot arms have admittance control [63].
3.11.2 Clinical outcomes

A pilot study with six hemiparetic subjects found that movements were comfortable and unimpeded. They were able to perform reaching movements for each level of assistance [63], [64]. As these studies collected qualitative data on user and therapist perception, they did not measure improvements in impairment or disability, nor were there controls.

3.12 NeReBot

3.12.1 Description

The Neuro-Rehabilitation-Robot (NeReBot) is a three DoF wire based robot (see Figure 3.10). It supports the arm through cables attached to overhead arms which are attached to a transportable C-frame. It is powered by three direct current (DC) motors at the top of the device. The NeReBot simulates hand-over-hand therapy by learning movements from therapists and then repeating these movements with clients. NeReBot has visual feedback through a monitor. Although much of the movement is passive, users can contribute to the movement by pushing or pulling. Therapists set the angular and linear position of the links according to the patient and exercise. There is an emergency stop that either the therapist or patient can use [65].
3.12.2 Clinical outcomes

In a RCT, 35 acute stroke patients received NDT therapy and robotic therapy. The control group received robotic therapy on their unimpaired arm and the experimental group received therapy on the impaired arm. Both groups improved in functional recovery, however the experimental group had statistically significantly less impairment even after three months and eight months [65].
3.13 ReoGo

3.13.1 Description

The ReoGo (Motorika Medical, Ltd, www.motorika.com) is a RRD that allows for rehabilitation in three dimensions. The device can move the user’s arm passively or actively. The arm or wrist of the user is strapped onto a large joystick-like end effector which is connected to a laptop computer. The end effector can also be a handgrip. The user is able to actively direct the robotic arm or passively be guided by the robotic device [66].

3.13.2 Clinical outcomes

In pilot studies with no control, it has been shown that the ReoGo (or Reo Therapy System) has been well received by stroke survivors. It was shown in one study with 10 sub acute stroke subjects, arm impairment and functionality increased significantly after 15 sessions [66], although all subjects simultaneously underwent standard daily rehabilitation sessions. In an
uncontrolled study 14 chronic stroke survivors showed statistically significant improvement after using the ReoGo [67].

3.14 Discussion

From the literature, we can see there are many upper limb RRDs which have been or which are currently being developed. However, few devices are commercially available and those that are available are not commonly used in clinics or hospitals [68]. Even fewer devices are being used in the home [69]. This may be due to factors such as lack of clinical evidence, limited functionality, cost constraints, safety concerns, equipment size, or usability issues [68].

Functionality is an important factor in a robotic rehabilitation device. There are two main types of devices for upper limb gross motor (shoulder/elbow) rehabilitation in the literature, exoskeleton devices wrap around the upper arm and lower arm, and end effector devices which are secured at the hand/wrist. End effector devices generally have less functionality than exoskeleton devices as they have two or three DoF, limiting how the device is able to simulate ADLs. Exoskeleton devices have more flexibility and ROM. Functionally, devices that use more senses would be more welcome – those with audiovisual displays as well as haptic displays may make rehabilitation more realistic, giving better options for proprioceptive feedback and sensorimotor rehabilitation.

In order for clinicians to accept RRDs, rehabilitation devices need to prove their clinical efficacy as well as attain benefits not easily achieved through conventional therapy [13]. Seven of the thirteen devices reviewed had RCTs – the MIT MANUS, the MIME, the ARM Guide, TWREX, Bi-Manu-Track, Rehaslide, and the NeReBot. Of these, the MIT MANUS, MIME, Bi-Manu-Track, and NeReBot showed statistically significant improvements over the controls. More clinical testing needs to be done on the other devices to determine their clinical advantages. Kwakkel has done a meta analysis on upper limb rehabilitation devices which indicate a significant moderate summary effect size in upper arm robotic rehabilitation with an overall change of 7-8% in motor control based on Fugl-Meyer assessment scale and Chedoke-McMaster Stroke Assessment Scale (assessment tools used to measure impairment and disability in those with neurological impairments)[10]. However there was no significant
improvement on ADL outcome based on the Functional Independence Measure (an assessment tool used to measure functional outcomes).

Safety concerns may increase as stroke survivors use robotic devices unsupervised. Many factors can determine the safety of a device. Generally backdrivable, impedance controlled devices are safer than admittance controlled devices. Haptic devices which are impedance controlled do not have as ‘hard’ of virtual surfaces as admittance controlled devices and are better able to simulate free air [70]. Non-actuated systems are generally safer than actuated systems, as they do not have any motors, which are liable to fail. End effectors devices may allow for too much freedom of the shoulder joint and may not be able to detect unnatural movement, whereas exoskeleton devices are more able to control for each joint. However, if the biomechanics of the exoskeleton are not done properly, the arm can be positioned in unnatural ways. The amount of force a device is able to produce can also become a safety issue. It is best that a RRD produce just the amount of force necessary and not too much more, especially when assisting a hemiparetic arm. This may especially become an issue when working with industrial robots that are able to produce large amounts of force.

Costs of robotic devices not only include the device, but system maintenance, training, and therapist set up time [71]. For example, the 2010 InMotion2 shoulder/elbow robot’s base price is $84,500 [72]. Initial costs are only the beginning. Devices with more DoF may not only cost more initially, but also end up costing more in maintenance as more motors and sensors need to be maintained. Studies have shown the effectiveness of rehabilitation robotics as being comparable to usual or intensive therapy [44], [56], [73], [74], as a result, many clinics and hospitals may find it more cost effective to hire a therapist over buying a rehabilitation robot. Systems which have intensive set up times may end up being more costly in the long run as therapist time must be used to set up the device.

RRDs need to be easy to use for patient safety reasons and for therapist and stroke survivor buy-in. Usability includes ease of set up and intuitive user interfaces. End effector devices tend to have easier set up in donning or doffing the device. Devices which need extensive therapist programming or training may also be dismissed they would take too much
time to set up. Software programs that require extensive set up time would also discourage extensive use. Devices that cannot be set up easily in the clinic would be even more challenging to use in a home environment.

Accessibility to rehabilitation is one of the prime motivations for the creation of these devices; therefore a device’s accessibility to stroke survivors must also be evaluated. Accessibility may include a device’s cost, portability, and home use. Costs may be prohibitive to smaller clinics and hospitals. Portability becomes an issue, when stroke survivors living in remote locations are not able to readily travel to clinics or hospitals. In addition, devices which are heavy or which have a large footprint may not be readily used in a typical hospital or clinic setting, and even less likely to be used in a home setting. End effector devices tend to be smaller, although this is not true in all cases.

In order to increase access to rehabilitation for stroke survivors, these robotic devices must be able to aid a therapist by decreasing workload and burden, and/or be usable in places where there may be difficulties in accessing a therapist, and be cost effective. Considerations such as good clinical outcomes, functionality, DoF, ROM, usability, safety, and accessibility are all important in designing a device that would be usable to both the stroke therapist and stroke survivor population.
Chapter 4. Observational Sessions with Stroke Therapists

This chapter describes observational sessions with stroke therapists to understand their workflow in terms of designing a RRD.

4.1 Research questions

1. Who are the people involved when stroke therapists treat stroke survivors?
2. How do therapists use their time while treating stroke survivors?
3. What objects/devices do therapists use in treating stroke survivors?
4. What is the treatment environment like?
5. What messages and services do therapists give to stroke survivors?

4.2 Ethnography

Ethnography incorporates tools such as participant observations, interviews, and questionnaires to understand people within their natural environment. Ethnography has recently been used in design to give insight to how people work, how they interact with each other, and what tools they use [75], [76].

To gain a better understanding of therapists’ work processes, their client interactions, and their workplace, informal observational sessions and interviews were conducted. Results of the observational sessions were used to inform the next phase of the study, which was an international survey of stroke therapists.

4.3 Methods

Four observational sessions with five stroke therapists and eight stroke survivors were conducted to gain an understanding of therapists’ interaction with stroke survivors and therapists’ workflow. Therapists were all occupational therapists (OTs) treating stroke survivors’ upper limbs. Sessions were conducted in inpatient and outpatient clinics at the Toronto Rehabilitation Institute (TRI) (Toronto, ON, Canada; www.torontorehab.on.ca) during regular working hours between November 2 and December 4, 2009. Some therapists were
interviewed before the session and some were interviewed after seeing their clients. The sessions were not video recorded or taped, however, notes were taken as the therapists interacted with their clients. Before each session, clients were asked permission to have a person observing. Only when permission was granted were they observed.

There are several ways to code or record ethnographic transactions. The POEMS (People, Objects, Environments, Messages, and Services) method was developed to be used in a large database that could code and search video for different studies [76]. This framework is used below to group different findings from observations and interviews, simply as a way to categorize observations. ‘People’ describes the people who are involved. ‘Objects’ are tools or items that are used by the people. ‘Environments’ describe the surroundings around the people. ‘Messages’ are the interactions and communication given by the people. ‘Services’ are the actions performed by those being observed. This method was used to report observations from the sessions.

4.4 Results

4.4.1 People

The people who were involved in these sessions included five (n=5) occupational therapists and eight (n=8) stroke survivor clients. Other therapists who were also involved included rehabilitation therapists and physiotherapists. Therapists were all employees of TRI. The stroke survivor clients included inpatients and outpatients and ranged in their Chedoke-McMaster Stroke Assessment Scale scores [77] from one to three out of seven (high impairment) for the hand and two to four out of seven for the arm (medium to high impairment). Some had other complicating illnesses such as arthritis, which affected their upper limb rehabilitation.

Many stroke survivors observed had issues of fatigue, spasticity and tone (both high and low). All had weakness in their upper limbs. Some had difficulties in planning certain movements. Others had difficulty with coordination. Some showed signs of neglecting their paretic side. Some had memory and cognitive challenges.
4.4.2 Objects

Wheelchairs were used to bring inpatients into the clinic where the occupational therapist was. Sometimes patients were transferred to a bed, but other times they would stand or remain in their wheelchair while receiving therapy. Stroke survivors came with their memory binders, which was divided into three sections – OT, PT (physiotherapy), SLP (speech and language pathology). In the OT section were written exercises, techniques and strategies to help the stroke survivor.

Clinicians would use objects found in the room to facilitate rehabilitation activities, such as cones, tables, poles. One item was often used in different ways with different clients.

Objects such as a phones, spoons, knives and pens were used to practice activities of daily living. Some of these objects were modified to allow the stroke survivor to better grip the handle. Tables were used to aid in standing and balance. Tabletops and ironing boards were also used in the horizontal and slanted positions (for adjustable tables) to practice sliding the hand forward and backward. Cones were given to clients to perform hand exercises with – to hold, turn, and release. Different sized balls and half spheres were also used to put weight on or squeeze. Bean bags were used to practice throwing in a bucket. Crafts such as train model kits were also used for fine motor skills. Molded splints and the Saebo Flex (www.saebo.com) were used to stretch out the client’s muscles. Some clients wore a splint many hours each day to maintain tissue length.

In the computer room there were several computers with different activities. The one therapist-client interaction observed consisted of cognitive rehabilitation activities. A rehabilitation device that connected to the computer was also shown. This device had adjustable tension which could allow for supination and pronation activities, for example playing simple games.

4.4.3 Environments

Three workspaces were observed in at two different locations of TRI. The workspace was generally shared with other clinicians. One workspace was specifically for clients who required
the use of a computer. Two other workspaces were generally used for physical rehabilitation activities.

There were often other activities going on at the same time in the same large room. At times there were other clinicians, such as physiotherapists, helping the same client. The room was not overly crowded, however there was not a lot of open space. In one room there was a kitchen setup in one corner to aid clients in doing realistic ADLs.

The computer area was quieter as there were no others using the computers at the time. There were several chairs around several desktop computers in an ‘L’ configuration.

4.4.4 Messages

Therapists would often give their clients verbal and visual reminders or cues in doing each activity. They would also give encouragement to their clients and use their hands to guide their clients’ movements. Therapists would physically cue clients using their hands, for example touching muscles that should be activated during an activity. Sometimes they would ask their clients what they could do to help their paretic arm do a certain activity, for example have the less impaired arm help the paretic arm. Clients were asked to use mental imagery and visualization to aid in their paretic arm movement. Therapists would bring awareness to the paretic arm, if their clients had inattention or neglect to that side. At the end they would have their clients write down in their memory books strategies for each challenging activity. Clients were told to move until they had pain and to stop if they encountered any pain. Generally therapists communicated to their clients to relax, as many of them had high tone.

There was a client who had limited English, which made communication difficult.

4.4.5 Services

The therapists would use their hands to cue clients to use certain muscles or to feel if the muscle was working. They would also position their clients’ arms or shoulders in a more correct position, if the arms were in an awkward position. Sometimes they would feel the shoulder for subluxation. They would massage their clients to help their clients relax their muscles if they had high tone. Therapists would make sure that their clients were rested.
enough, not waiting until their clients were too tired. If a client was using a splint, the therapist would take it off before commencing with treatment.

Therapists generally interacted with their clients for about an hour. This included going through their home activities, examining the condition of their arm, instructions for additional exercises, and therapeutic interventions for the arm.

4.5 Discussion

Although the observation sessions were limited to occupational therapists in a rehabilitation hospital setting, they provided good insight into therapists’ workflow, interactions with clients, and workspace. This information was used to inform the design of the RRD.

The observed space was generally shared and limited. Therefore any therapeutic device would need to fit into a limited space. Large RRDs may have trouble in fitting into such a space, and may be a hindrance to therapist workflow if therapists need to work around them. As many therapists shared the workspace, a portable device would be ideal. A portable device could be transferred from station to station, or clinic to clinic. Therapists could use a portable device in different work areas in a clinic and not have to be limited to one workstation. In addition, as patients were often wheeled in via wheelchair, a good device would need to be compatible with a wheelchair. Therapists would not need to transfer patients to a certain seat or bed, if the device was compatible with wheelchair use.

The therapists observed liked to physically cue their clients. They used their hands to position clients’ arms and hands and cue clients’ muscles. A good rehabilitation system would need to be compatible with therapist cueing, which would mean the system would need to be safe for two users: the therapist and the stroke survivor. Some RRDs are meant to be used without therapist intervention, in essence to ‘free up the therapist’. Therapists, however, are accustomed to working by how a muscle feels and not by quantitative forces a robotic device could deliver. Until this sense of touch is quantified, therapists may still want to physically
interact with their client, even while their clients are using a RRD. Physical cueing may be one way therapists use to evaluate the efficacy of a RRD.

As different everyday objects are incorporated into stroke therapy to practice activities of daily living, a RRD could also be designed to use different everyday objects. This would aid the transition from therapy to ADLs. As therapists used different planes of motion to perform their therapy, a RRD would need to be adaptable enough to use different planes of motion to simulate the therapy that is currently being given. The robotic device should be adjustable to allow for different planes of movement or allow for movement in at least three dimensions.

As therapy time was limited, time for setting up a device, if used during a typical therapy session, would also need to be very limited. Extensive time donning and doffing a device would cut into valuable therapy time. Therefore, a useful device would have minimal set up time. If a device is meant to be used in the home, the set up would also need to be simple.

Cognitive activities could be incorporated into the system by means of puzzles and activities of daily living that are currently being used for cognitive rehabilitation. Physical and cognitive rehabilitation could go together, thus saving therapists’ time. Computer and robotic devices can be easily coupled to accomplish this. An RRD system with VR could also aid stroke survivors in using mental imagery in showing a computer visualization of what therapists would like their clients to do. Computerized systems could also bring awareness to a side that has suffered from inattention or neglect by giving audio and visual cues to that side.

During the observation sessions therapists would often ask their clients if they were in pain. A device that could sense pain in a stroke survivor could aid therapists in knowing when to continue therapy or when to stop. Some therapists remarked that their clients would sometimes adhere to the saying, “no pain, no gain”, but according to therapists, stroke patients should not work through their pain. Position sensors could also aid therapists in detecting incorrect arm positions or shoulder subluxation, allowing therapists to focus more on therapy than on checking if the arm is in an incorrect position.

A RRD would need to address the special needs of stroke survivors. It could address fatigue issues by monitoring fatigue. It would need end effectors which could properly secure
the hand. An assistive feature would be good for those with higher impairments in the arm. Having haptic and visual feedback may aid with coordination training. A vibrating end effector may aid in bringing a person’s attention to a neglected side.

Computerized robotic rehabilitation systems could easily incorporate features such as multiple languages to allow for better communication between therapist and client if there is a language barrier. In addition, videos of exercises may be shown to demonstrate proper at home exercise. A device could also incorporate the use of the memory binder, by suggesting activities or having a virtual memory binder that can be kept online and/or printed out.

4.6 Limitations

The observations sessions were limited to observing occupational therapists interactions with their stroke clients at a rehabilitation hospital facility in one city. Thus they did not include at home therapy, therapy in a nursing home environment, or therapy in a small clinic. Therapy in a home setting may not involve all of the tools and devices a rehabilitation hospital may offer, but rather use tools and objects which may be readily available at home. Therapy in a small clinic or nursing may also not have as many tools as in a rehabilitation hospital. In addition, they may be more limited in space. The observations also did not include rehabilitation therapists or physiotherapist interactions, which may be different than those of occupational therapists. In addition, therapists from different countries may have different approaches to therapy. More observations of different types of therapists in different environments are necessary to draw better conclusions.
Chapter 5. Therapist Survey

This chapter describes a therapist survey conducted to understand therapists’ current practices and requirements for a RRD. Note: Parts of this chapter have been submitted for publication [78], [79].

5.1 Past surveys in the literature

Past surveys have been used to look at desired functions of rehabilitation robots or current stroke rehabilitation practices. Several survey studies were conducted with people with disabilities to look into their desired functions for robotic arm manipulators and powered orthoses [71]. Other studies have looked at therapist practices of stroke rehabilitation [80-84]. However, these were limited in the type of therapist from whom data were collected, that is, only physiotherapists, and the survey were not explicitly concerned with the design of a RRD for therapy. One survey conducted on current clinical practices in stroke rehabilitation that did include occupational therapists [85]; however it was limited in terms of region (Kansas and Missouri, USA). To the author’s knowledge there has been only one study on design requirements for rehabilitation robots from the perspective of therapists [68]. However, the sample size was small (n=17) and it was also limited to a particular region (Ontario, Canada).

5.2 Research questions

1. How do stroke therapists currently treat the upper limbs of stroke survivors?
2. What are stroke therapists’ aims of rehabilitation for the upper limb?
3. How do stroke therapists facilitate movement during treatment?
4. How do stroke therapists manage tone in stroke survivors?
5. What types of biofeedback do therapists require?
6. What are therapists’ requirements for an upper limb RRD?
7. How much would therapists pay for an upper limb RRD for stroke survivors?
5.3 Methods

An online survey was used to understand the general requirements of quality stroke therapy from the perspective of stroke therapists, as well as the requirements for a RRD that would be able to deliver the same level of quality care as would a therapist. The first phase of this project surveyed therapists in an attempt to gain a broad understanding of current rehabilitation methods and stroke rehabilitation aims, as well as to understand what features would be desirable in an upper limb rehabilitation robot. Features polled included movement patterns for the device, as well as levels of assistance and feedback, interfaces for therapists and/or stroke survivors, types of interactive activities, and accessibility (size, transportability, and cost). Results from the survey were used to inform subsequent phases of the research.

5.3.1 Questionnaire

A questionnaire was designed based on a previous survey [86], observational sessions of therapists and stroke patients during rehabilitation (see Chapter 4), and interviews with three occupational therapists who worked with stroke survivors. The final version of the questionnaire was reviewed for content and language by an occupational therapist with 30 years of experience working in neurorehabilitation. The survey was specifically targeted at upper limb rehabilitation and was divided into six sections: therapist background and treatment approaches, aims of rehabilitation, muscle tone management, facilitation of movement, sensory feedback, and potential attributes of a robotic rehabilitation device.

In order to ensure that the RRD design would be appropriate, it was important to understand current clinical practices to guide the types of therapy with which the robotic device could assist. Different theories and methods of therapy influence the type of therapy given and hence the type of robotic device designed to complement current clinical practices. Aims of rehabilitation were an important factor in designing the user interfaces and types of movements that could be involved. Through the interviews, it was found that abnormal muscle tone was an issue that many therapists needed to deal with and therefore an issue the robotic device may need to accommodate. Knowledge of how therapists facilitate movement and their attitudes toward functional movements were also important to understand so that
the robot would aid movement appropriately. Rehabilitation may also include improving sensory awareness and biofeedback, and whether or not these were commonly used would be important to the design of a new robot. Finally, the design of the rehabilitation device included physical aspects such as type of user interface, size of the device, therapeutic resistance, and type of handholds.

Based on the above information, 85 questions were developed for the questionnaire (see Appendix A). Most questions were either closed-ended questions (multiple choice), or questions based on a five point Likert scale, which gauged level of agreement (‘strongly disagree’, ‘somewhat disagree’, ‘neutral’, ‘somewhat agree’, or ‘strongly agree’) or feelings of importance (‘very unimportant’, ‘somewhat unimportant’, ‘neutral’, ‘somewhat important’, or ‘very important’) of an item.

Additionally, the rehabilitation robot requirement section asked respondents to rank the top five attributes from two different lists of requirements, the top five from one list and the top five from another list. Finally, the respondents were asked to imagine a customizable robotic rehabilitation device with variable resistance that provided motivational activities and was appropriate for use in a clinic or a home setting. Respondents were given a list of features and functions and asked to rate how useful they thought each would be using a five-point Likert scale (for agreement).

Respondents were given opportunities to provide other comments in several sections and at the end of the overall questionnaire. The final version of the questionnaire, as well as the information and consent form was approved by the appropriate institutional research ethics boards.

5.3.2 Survey distribution

The survey was distributed to both physiotherapists and occupational therapists in Australia, Canada, the United Kingdom, and the USA. Those working in other countries could have also responded to the survey, as the survey was online and open to anyone. In order to protect the confidentiality of respondents, as well as respect legal requirements in different
countries, information about the survey was sent to the respective professional organizations and email list services to distribute as they saw fit, see Appendix B. The survey was open until a minimum of 200 people responded or until two months had passed for a confidence level of 95% and a confidence interval of 7%, calculated as in equation (5-1) [87]:

$$n = \frac{z^2 \times p \times (1-p)}{d^2}$$  \hspace{1cm} (5-1)

Where \( n \) is the sample size for categorical data, \( z \) is the standard deviation units (using a confidence interval of 95% \( z=1.96 \)). The variable \( p \) is the estimate of variance, for a worst case scenario would be 0.5. The variable \( d \) stands for the confidence interval, or acceptable margin of error, in this case 0.07. Typically the acceptable margin of error would be 0.05, however as the data were used to inform the next phase of the study, these numbers were viewed as sufficient. Information about the research, an informed consent form, and the survey itself were posted online. Participants had to indicate consent by checking “Yes! I would like to participate in this survey” before answering the survey questions. The survey was distributed from April 2010 to June 2010 in Canada, the United Kingdom, and the USA, and from June 2010 to July 2010 in Australia.

### 5.3.3 Survey analysis

Categorical data were reported with descriptive statistics, using percentages. Ordinal categorical data (Likert scale data) were reported as median (the middle value, where there were equal numbers of responses above and below this value), percentage of combined agreement (‘strongly agree’ and ‘somewhat agree’) or feeling of importance (‘very important’ and ‘somewhat important’), and consensus between respondents. As the data were used to inform focus groups, it was felt that those items which respondents deemed important or agreed with would be of more significance. Responses were therefore reduced to the nominal level by combining responses into two levels: disagreement and agreement (‘strongly disagree’ and ‘somewhat disagree’, ‘strongly agree’ and ‘somewhat agree’), or feeling of importance and unimportance (‘very important’ and somewhat important’, ‘very unimportant’ and ‘somewhat unimportant’).
Survey responses were transferred to Microsoft Excel (www.microsoft.com) for analysis. A calculation of consensus was used to reflect the consensus amongst respondents with a consensus of 0% signifying that no two people chose the same answer and 100% signifying absolute consensus (all respondents chose the same answer) [88]. Consensus was calculated using equation (5-2).

\[
\text{Consensus}(X) = 1 + \sum_{i=1}^{n} p_i \log_2 \left( 1 - \frac{|x_i - \mu_x|}{d_x} \right)
\]  

(5-2)

In equation (5-2), \( X \) indicates the finite discrete random variable (the Likert scale choices), \( p_x \) is the probability distribution, \( \mu_x \) is the mean and \( d_x \) is the width of \( X \). Four raters were used to categorize answers that had ambiguous categories, namely to assign categories to robot attributes when respondents wrote out the wording of an attribute rather than its associated list number. These raters came from a background of biomedical engineering and occupational therapy. Cohen’s Kappa was used to estimate inter-rater reliability of these four raters, equation (5-3) [89], where \( \Pr(a) \) is the relative observed agreement and \( \Pr(e) \) is the hypothetical chance agreement.

\[
\kappa = \frac{\Pr(a) - \Pr(e)}{1 - \Pr(e)}
\]  

(5-3)

As the most of the data were ordinal or categorical, Pearson’s chi squared significance test, see equation (5-3) was used to see if there were any relationship between the demographics of the therapists (profession, experience, country) and responses in other sections [90]. In equation (5-4), \( O \) = observed, \( E \) = expected values. The responses strongly disagree and disagree were combined, as well as strongly agree and agree (combined), very important and somewhat important (combined), and very unimportant and somewhat unimportant (combined) to ensure reasonable sample size for comparison. Adequate sample size was at least a frequency of five expected in each cell [91]. Countries that had less than five respondents in 80% of the cells were taken out of the chi squared analysis for comparisons between countries as there were insufficient data.
\[ X^2 = \sum \frac{(O-E)^2}{E} \]

where \[ E = \frac{\text{row total} \times \text{column total}}{\text{overall total}} \]

5.4 Results

5.4.1 Demographics

The survey was viewed 696 times and of the 320 respondents who started the survey, a total of 237 completed it (completion was considered to be when respondents responded to 85% of the questions, which was arbitrarily chosen), for a completion rate of 74%. Surveys whose respondents had less than one year of experience in stroke therapy were excluded, leaving 233 surveys that were analyzed. Calculations were based on the actual number of respondents for that section.

Most respondents were either physiotherapists (72%) or occupational therapists (27%) who held a Bachelor’s degree (61%) or higher (33%). The respondents who responded worked in different countries: Australia (48%), Canada (28%), the USA (15%), the Republic of Ireland or United Kingdom (6%), Sweden (1%), Switzerland (<1%), Columbia (<1%), and Israel (<1%). Two respondents did not indicate their country of practice. Only Australia, Canada, and USA had enough respondents to be used in a chi-squared analysis concerning differences between countries.

Therapists’ reported experience in providing stroke rehabilitation included 55% who had worked with stroke survivors for more than 10 years, 18% who had worked with them for 6-10 years, and 27% who had worked with them for 1-5 years. In terms of place of rehabilitation, respondents had worked in: a rehabilitation hospital (81%); an inpatient, acute care setting (64%); an outpatient clinic (52%); the stroke survivor’s home (42%); and a long term care facility (20%). In addition some had worked in private practice, schools, research centres, in the community, and in complex continuing care.
5.4.2 Current methods of stroke treatment and assessment

There were many different types of therapy methods that were practiced. Respondents used repetitive task training (88%), motor relearning (MR) (76%), neurodevelopmental therapy/Bobath (NDT) (64%), electrical stimulation (50%), high intensity or practice (50%), mental practice with motor imagery (45%), constraint-induced movement therapy (CIMT) (44%), proprioceptive neuromuscular facilitation (PNF) (42%), and splinting/orthosis (42%). Some used joint position biofeedback (11%) and electromyographic biofeedback (EMG) (9%), but few had used robot-assisted therapy in the past (6%). Other therapy methods currently being used included the Feldenkrais Method, adaptation, mirror therapy, virtual reality, positioning and weight bearing stabilization, bimanual training, and strengthening exercises.

Respondents reported using many different types of assessment tools to assess stroke survivors. The Motor Assessment Scale was used by 56%, the Chedoke-McMaster scale was used by 38%, the Fugl-Meyer assessment scale was used by 15%, the National Institutes of Health stroke scale by 13%, the Action Research Arm Test by 12%, and the Wolf Motor Function by 8% of respondents. Some did not use standardized tests, but used their own assessments or functional assessments.

Current methods of stroke treatment differed significantly \( p<0.05 \) by country in all aspects except joint biofeedback, mental imagery, splinting/orthosis use, and repetitive task training. Figure 5-1 shows the difference in usage of selected therapeutic approaches.
Figure 5-1. Therapy approach comparing therapists’ country of practice.
*Statistically significant difference (p<0.05).

5.4.3 Aims of rehabilitation

The survey asked how important they would rate certain aims of rehabilitation on a five-point Likert scale of importance. Table 5-1 shows the median scores, combined percentages of those who believed the item was ‘important’ and the consensus score.
Table 5-1. Aims of rehabilitation: on a five-point Likert importance scale
Median score, percentage of respondents who rated the aim as ‘important’, and percentage in consensus

<table>
<thead>
<tr>
<th>Aims of rehabilitation</th>
<th>Median</th>
<th>% Important</th>
<th>Consensus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facilitate functional activities n=232</td>
<td>Very Important</td>
<td>95%</td>
<td>70%</td>
</tr>
<tr>
<td>Prevent further injury or complications n=233</td>
<td>Very Important</td>
<td>93%</td>
<td>69%</td>
</tr>
<tr>
<td>Improve co-ordination n=232</td>
<td>Very Important</td>
<td>91%</td>
<td>60%</td>
</tr>
<tr>
<td>Prevent secondary tissue changes n=232</td>
<td>Very Important</td>
<td>90%</td>
<td>68%</td>
</tr>
<tr>
<td>Learn normal muscle movement n=231</td>
<td>Very Important</td>
<td>87%</td>
<td>68%</td>
</tr>
<tr>
<td>Restore alignment of the joints n=233</td>
<td>Somewhat Important</td>
<td>82%</td>
<td>66%</td>
</tr>
<tr>
<td>Learn how to isolate muscle activation n=231</td>
<td>Somewhat Important</td>
<td>69%</td>
<td>63%</td>
</tr>
<tr>
<td>Learn compensational strategies n=227</td>
<td>Somewhat Important</td>
<td>53%</td>
<td>55%</td>
</tr>
</tbody>
</table>

In the free text comments section, there were many respondents who commented that aims of rehabilitation differed between stroke survivors and are dependent on different phases of rehabilitation. Some respondents commented that learning compensatory strategies was used as a last resort. Another respondent commented that while some of the aims of rehabilitation listed in Table 5-1 were important, they may not be possible.

There were not many statistically significant differences between countries with regards to aims of rehabilitation. The only statistically significant difference (p<0.05) between countries was in ‘learn how to isolate muscle activation’ with therapists from Australia finding it more important than those in Canada or the USA.

5.4.4 Managing muscle tone
The survey asked how important certain items were with regards to managing muscle tone during therapy. Choices were out of a five-point Likert scale for importance. The median scores, combined percentages of those who believed the item was ‘important’, and the consensus score are reported in Table 5-2. There was not a significant difference in answers in regards to country of practice. Free text comments on this section found that although tone was important, it depended on other factors, and could not be isolated as a single factor.
Table 5-2. Managing muscle tone: on a five point Likert importance scale
Median score, percentage of respondents indicating 'important', and percentage in consensus

<table>
<thead>
<tr>
<th>Tone management</th>
<th>Median</th>
<th>% Important</th>
<th>Consensus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreasing tone is important when facilitating movement n=231</td>
<td>Somewhat</td>
<td>77%</td>
<td>58%</td>
</tr>
<tr>
<td>Functional tasks may improve without changes in tone n=229</td>
<td>Somewhat</td>
<td>76%</td>
<td>71%</td>
</tr>
<tr>
<td>Strategies to move from closed chain to open chain n=228</td>
<td>Somewhat</td>
<td>72%</td>
<td>68%</td>
</tr>
<tr>
<td>Movement should be graded for those with high tone n=226</td>
<td>Somewhat</td>
<td>70%</td>
<td>64%</td>
</tr>
<tr>
<td>Movement should be slow for those with high tone n=227</td>
<td>Somewhat</td>
<td>52%</td>
<td>57%</td>
</tr>
</tbody>
</table>

5.4.5 Sensory feedback

Survey participants were asked how much they agree with certain items were with regards to sensory feedback. Choices were out of a five-point Likert scale of agreement. The median scores, combined percentages of those who agreed with the statement, and the consensus score are reported in Table 5-3. In all, respondents somewhat agreed that biofeedback was useful and there were no statistically significant differences between countries.

Table 5-3. Sensory feedback: on a five-point Likert agreement scale
Median score, percentage of respondents indicating 'agree', and percentage in consensus

<table>
<thead>
<tr>
<th>Sensory feedback</th>
<th>Median</th>
<th>% Agree</th>
<th>Consensus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofeedback on muscle activated would be a useful tool for the stroke survivor n=232</td>
<td>Somewhat Agree</td>
<td>77%</td>
<td>77%</td>
</tr>
<tr>
<td>Biofeedback on muscle activation would be a useful tool for me n=231</td>
<td>Somewhat Agree</td>
<td>71%</td>
<td>72%</td>
</tr>
<tr>
<td>Biofeedback is an important tool to use n=232</td>
<td>Somewhat Agree</td>
<td>64%</td>
<td>69%</td>
</tr>
<tr>
<td>Biofeedback on joint position would be a useful tool for the stroke survivor n=228</td>
<td>Somewhat Agree</td>
<td>61%</td>
<td>72%</td>
</tr>
<tr>
<td>Biofeedback on joint position would be a useful tool for me n=232</td>
<td>Somewhat Agree</td>
<td>54%</td>
<td>66%</td>
</tr>
</tbody>
</table>

5.4.6 Facilitation of movement

Survey participants were asked how much they agreed with certain statements regarding the facilitation of movement. Choices were given out of a five-point Likert scale of agreement.
Table 5-4 lists the median scores, percentage of respondents who chose ‘agree’, and the consensus.

**Table 5-4. Facilitation of movement: on a five point Likert agreement scale**  
Median score, percentage of respondents indicating ‘agree’, and percentage in consensus

<table>
<thead>
<tr>
<th>Facilitation of movement</th>
<th>Median</th>
<th>%Agree</th>
<th>Consensus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke survivors need task oriented training and practice n=232</td>
<td>Strongly Agree</td>
<td>99%</td>
<td>89%</td>
</tr>
<tr>
<td>Stroke survivors need context-specific cognitive learning, feedback, and practice n=232</td>
<td>Strongly Agree</td>
<td>94%</td>
<td>79%</td>
</tr>
<tr>
<td>Trunk stability is a prerequisite for quality upper arm movement n=233</td>
<td>Strongly Agree</td>
<td>91%</td>
<td>70%</td>
</tr>
<tr>
<td>Stroke survivors need regular one-on-one therapy sessions n=233</td>
<td>Somewhat Agree</td>
<td>89%</td>
<td>72%</td>
</tr>
<tr>
<td>Active motor sequences that are performed repetitively within a single training session with a clear functional goal will aid in recovery of that functional task n=232</td>
<td>Somewhat Agree</td>
<td>86%</td>
<td>72%</td>
</tr>
<tr>
<td>High intensity of focused therapy will allow the stroke survivor to recover sooner n=232</td>
<td>Somewhat Agree</td>
<td>85%</td>
<td>74%</td>
</tr>
<tr>
<td>Strength training is important to incorporate in any stroke rehabilitation program n=231</td>
<td>Somewhat Agree</td>
<td>85%</td>
<td>69%</td>
</tr>
<tr>
<td>Activating movements bilaterally aids in recovery of the affected side n=233</td>
<td>Somewhat Agree</td>
<td>79%</td>
<td>76%</td>
</tr>
<tr>
<td>Improving a client’s ability to move does not necessarily improve the ability to perform functional tasks n=232</td>
<td>Somewhat Agree</td>
<td>78%</td>
<td>67%</td>
</tr>
<tr>
<td>Where the potential for recovery of normal movement exists, I would delay performing certain activities if they reinforce abnormal movement patterns n=232</td>
<td>Somewhat Agree</td>
<td>68%</td>
<td>54%</td>
</tr>
<tr>
<td>Few high quality movements are more important than many poor quality movements n=231</td>
<td>Somewhat Agree</td>
<td>63%</td>
<td>59%</td>
</tr>
<tr>
<td>Electrical stimulation is a good way to increase muscle movement n=233</td>
<td>Somewhat Agree</td>
<td>52%</td>
<td>68%</td>
</tr>
<tr>
<td>Passive upper limb movement will naturally lead to active upper limb movement n=226</td>
<td>Somewhat Disagree</td>
<td>6%</td>
<td>66%</td>
</tr>
</tbody>
</table>

Figure 5-2 shows a comparison of therapist country of practice in the ‘Facilitation of movement’ section. American and Canadian therapists were more likely to agree with ‘activating movements bilaterally aids in recovery of the affected side’ improves recovery, whereas Australian therapists would more likely agree with ‘electrical stimulation is a good way to increase muscle movement’. Canadian therapists were less likely than the other countries to agree with the ‘high intensity’ statement and US therapists were more likely to
agree with the ‘passive upper limb movement will naturally lead to active upper limb movement’ statement.

**Facilitation of movement by country of practice**

<table>
<thead>
<tr>
<th>Statement</th>
<th>Australia</th>
<th>Canada</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke survivors need task oriented training and practice</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Stroke survivors need context-specific cognitive learning, feedback, and practice</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Stroke survivors need regular one-on-one therapy sessions</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Trunk stability is a prerequisite for quality upper arm movement</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>High intensity of focused therapy will allow the stroke survivor to recover sooner*</td>
<td>90%</td>
<td>80%</td>
<td>70%</td>
</tr>
<tr>
<td>Repetitive active sequences in a session with a functional goal will aid in task recovery †</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Strength training is important to incorporate in any stroke rehabilitation program*</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Activating movements bilaterally aids in recovery of the affected side</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Improving a client’s ability to move does not necessarily improve the ability to perform functional tasks</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Delay activities if they reinforce abnormal movement patterns when normal recovery is possible †</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Few high quality movements are more important than many poor quality movements</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Electrical stimulation is a good way to increase muscle movement*</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Passive upper limb movement will naturally lead to active upper limb movement*</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>

*Statistically significant (p<0.05). †Wording changed to fit graph

**Figure 5-2. Differences between countries in the section "Facilitation of movement"**
Table 5.5. Robotic rehabilitation device features: on a five-point Likert agreement scale
Median scores, percentage of respondents in agreement, and percentage in consensus

<table>
<thead>
<tr>
<th>Robotic rehabilitation device</th>
<th>Median</th>
<th>% Agree</th>
<th>Consensus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be usable in a seated position n=232</td>
<td>Strongly Agree</td>
<td>99%</td>
<td>86%</td>
</tr>
<tr>
<td>Allow different handholds for the hand n=232</td>
<td>Strongly Agree</td>
<td>97%</td>
<td>81%</td>
</tr>
<tr>
<td>Adjusts resistance based on client performance n=233</td>
<td>Strongly Agree</td>
<td>96%</td>
<td>81%</td>
</tr>
<tr>
<td>Allow for movement in the sagittal plane n=231</td>
<td>Strongly Agree</td>
<td>95%</td>
<td>76%</td>
</tr>
<tr>
<td>Maintain proper joint alignment n=232</td>
<td>Strongly Agree</td>
<td>95%</td>
<td>78%</td>
</tr>
<tr>
<td>Allow for movement in the transverse plane n=232</td>
<td>Strongly Agree</td>
<td>94%</td>
<td>76%</td>
</tr>
<tr>
<td>Be usable in a standing position n=233</td>
<td>Strongly Agree</td>
<td>94%</td>
<td>76%</td>
</tr>
<tr>
<td>Contain modular units with different functions n=233</td>
<td>Strongly Agree</td>
<td>93%</td>
<td>77%</td>
</tr>
<tr>
<td>Be able to facilitate many arm movements n=233</td>
<td>Strongly Agree</td>
<td>93%</td>
<td>76%</td>
</tr>
<tr>
<td>Have virtual ADL specific activities n=231</td>
<td>Strongly Agree</td>
<td>92%</td>
<td>77%</td>
</tr>
<tr>
<td>Be a compact device n=233</td>
<td>Strongly Agree</td>
<td>91%</td>
<td>76%</td>
</tr>
<tr>
<td>Be transportable from a clinic to a home n=232</td>
<td>Strongly Agree</td>
<td>91%</td>
<td>76%</td>
</tr>
<tr>
<td>Have a flexible handhold n=230</td>
<td>Somewhat Agree</td>
<td>90%</td>
<td>76%</td>
</tr>
<tr>
<td>Give biofeedback to the client n=232</td>
<td>Strongly Agree</td>
<td>90%</td>
<td>75%</td>
</tr>
<tr>
<td>Be a useful tool for stroke survivors to use at home n=233</td>
<td>Strongly Agree</td>
<td>88%</td>
<td>69%</td>
</tr>
<tr>
<td>Provide arm stability n=232</td>
<td>Strongly Agree</td>
<td>87%</td>
<td>74%</td>
</tr>
<tr>
<td>Provide hand stability n=232</td>
<td>Somewhat Agree</td>
<td>86%</td>
<td>73%</td>
</tr>
<tr>
<td>Have fun activities that may not necessarily be task specific</td>
<td>Somewhat Agree</td>
<td>82%</td>
<td>73%</td>
</tr>
<tr>
<td>Give biofeedback to the therapist n=233</td>
<td>Somewhat Agree</td>
<td>81%</td>
<td>73%</td>
</tr>
<tr>
<td>Once dispatched, requires little adjustment from therapists</td>
<td>Somewhat Agree</td>
<td>79%</td>
<td>68%</td>
</tr>
<tr>
<td>Requires specific adjustment from the therapist to ensure good fit</td>
<td>Somewhat Agree</td>
<td>76%</td>
<td>70%</td>
</tr>
<tr>
<td>Have a handhold the client would be able to move around</td>
<td>Somewhat Agree</td>
<td>74%</td>
<td>74%</td>
</tr>
<tr>
<td>Have separate interfaces for therapists and clients n=233</td>
<td>Somewhat Agree</td>
<td>69%</td>
<td>70%</td>
</tr>
<tr>
<td>Be an exoskeleton that will help control each joint n=232</td>
<td>Somewhat Agree</td>
<td>69%</td>
<td>74%</td>
</tr>
<tr>
<td>Be usable in a recumbent position n=233</td>
<td>Somewhat Agree</td>
<td>63%</td>
<td>65%</td>
</tr>
<tr>
<td>Provide trunk stability n=233</td>
<td>Somewhat Agree</td>
<td>63%</td>
<td>65%</td>
</tr>
<tr>
<td>Have predefined buttons n=231</td>
<td>Somewhat Agree</td>
<td>55%</td>
<td>72%</td>
</tr>
<tr>
<td>Have a touch-screen n=232</td>
<td>Somewhat Agree</td>
<td>54%</td>
<td>67%</td>
</tr>
<tr>
<td>Have a keyboard and mouse n=232</td>
<td>Neutral</td>
<td>20%</td>
<td>76%</td>
</tr>
</tbody>
</table>
### Table 5-6. Therapist ranking of most important attributes of a robotic rehabilitation device

#1 indicating most important attribute, #2 next important, #3 third important, #4 fourth important, #5 fifth important, combined total percentage of therapist ranking attribute in the top attributes section

<table>
<thead>
<tr>
<th>Robotic rehabilitation device rankings n=218</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be able to facilitate many arm movements</td>
<td>29%</td>
<td>20%</td>
<td>14%</td>
<td>11%</td>
<td>6%</td>
<td>81%</td>
</tr>
<tr>
<td>Be usable in a seated position</td>
<td>15%</td>
<td>13%</td>
<td>17%</td>
<td>13%</td>
<td>10%</td>
<td>68%</td>
</tr>
<tr>
<td>Give biofeedback to the client</td>
<td>32%</td>
<td>11%</td>
<td>7%</td>
<td>6%</td>
<td>7%</td>
<td>64%</td>
</tr>
<tr>
<td>Have virtual ADL specific activities</td>
<td>27%</td>
<td>12%</td>
<td>11%</td>
<td>8%</td>
<td>4%</td>
<td>62%</td>
</tr>
<tr>
<td>Be a useful tool for stroke patients to use at home</td>
<td>35%</td>
<td>6%</td>
<td>6%</td>
<td>8%</td>
<td>5%</td>
<td>60%</td>
</tr>
<tr>
<td>Adjusts resistance based on client performance</td>
<td>5%</td>
<td>13%</td>
<td>20%</td>
<td>14%</td>
<td>8%</td>
<td>60%</td>
</tr>
<tr>
<td>Contain modular units with different functions</td>
<td>9%</td>
<td>14%</td>
<td>14%</td>
<td>10%</td>
<td>9%</td>
<td>56%</td>
</tr>
<tr>
<td>Maintain proper joint alignment</td>
<td>11%</td>
<td>14%</td>
<td>12%</td>
<td>9%</td>
<td>8%</td>
<td>55%</td>
</tr>
<tr>
<td>Be a compact device</td>
<td>5%</td>
<td>11%</td>
<td>9%</td>
<td>10%</td>
<td>10%</td>
<td>45%</td>
</tr>
<tr>
<td>Allow for different handholds</td>
<td>3%</td>
<td>9%</td>
<td>8%</td>
<td>13%</td>
<td>8%</td>
<td>40%</td>
</tr>
<tr>
<td>Be usable in a standing position</td>
<td>0%</td>
<td>12%</td>
<td>8%</td>
<td>10%</td>
<td>9%</td>
<td>39%</td>
</tr>
<tr>
<td>Provide arm stability</td>
<td>3%</td>
<td>7%</td>
<td>11%</td>
<td>10%</td>
<td>6%</td>
<td>38%</td>
</tr>
<tr>
<td>Be transportable from a clinic to a home</td>
<td>3%</td>
<td>10%</td>
<td>5%</td>
<td>10%</td>
<td>10%</td>
<td>37%</td>
</tr>
<tr>
<td>Have fun activities that may not necessarily be task specific</td>
<td>2%</td>
<td>9%</td>
<td>9%</td>
<td>5%</td>
<td>10%</td>
<td>35%</td>
</tr>
<tr>
<td>Once dispatched, requires little adjustment from therapists</td>
<td>1%</td>
<td>5%</td>
<td>7%</td>
<td>8%</td>
<td>9%</td>
<td>30%</td>
</tr>
<tr>
<td>Give biofeedback to the therapist</td>
<td>3%</td>
<td>10%</td>
<td>1%</td>
<td>4%</td>
<td>4%</td>
<td>22%</td>
</tr>
<tr>
<td>Have a flexible handhold</td>
<td>1%</td>
<td>3%</td>
<td>5%</td>
<td>4%</td>
<td>7%</td>
<td>20%</td>
</tr>
<tr>
<td>Be an exoskeleton that will help control each joint</td>
<td>4%</td>
<td>1%</td>
<td>4%</td>
<td>5%</td>
<td>4%</td>
<td>18%</td>
</tr>
<tr>
<td>Provide hand stability</td>
<td>0%</td>
<td>2%</td>
<td>4%</td>
<td>5%</td>
<td>7%</td>
<td>18%</td>
</tr>
<tr>
<td>Require specific adjustments from the therapist to ensure a</td>
<td>1%</td>
<td>4%</td>
<td>4%</td>
<td>3%</td>
<td>5%</td>
<td>17%</td>
</tr>
<tr>
<td>Have separate interfaces for therapists and clients</td>
<td>0%</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>8%</td>
<td>16%</td>
</tr>
<tr>
<td>Provide trunk stability</td>
<td>2%</td>
<td>3%</td>
<td>4%</td>
<td>4%</td>
<td>2%</td>
<td>15%</td>
</tr>
<tr>
<td>Allow for movement in the sagittal plane</td>
<td>0%</td>
<td>1%</td>
<td>3%</td>
<td>5%</td>
<td>5%</td>
<td>14%</td>
</tr>
<tr>
<td>Have a handhold the client would be able to move around</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>4%</td>
<td>5%</td>
<td>13%</td>
</tr>
<tr>
<td>Allow for movement in the transverse plane</td>
<td>0%</td>
<td>1%</td>
<td>2%</td>
<td>2%</td>
<td>6%</td>
<td>11%</td>
</tr>
<tr>
<td>Have a touch-screen</td>
<td>0%</td>
<td>1%</td>
<td>2%</td>
<td>2%</td>
<td>6%</td>
<td>11%</td>
</tr>
<tr>
<td>Be usable in a recumbent position</td>
<td>0%</td>
<td>2%</td>
<td>2%</td>
<td>1%</td>
<td>4%</td>
<td>10%</td>
</tr>
<tr>
<td>Have predefined buttons</td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>Have a keyboard and mouse</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Other</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

### 5.4.7 Robotic rehabilitation device requirements

Table 5-5 shows the device requirements that were presented in the survey along with the respondents’ median selection, percentage in agreement with the statement, and consensus for each. Only one item (having a keyboard and mouse) had a statistically significant
difference between countries of practice. In addition to indicating their level of agreement regarding the inclusion of the features listed in Table 5-5, respondents were asked to rate which features they considered to be the top five most important in a rehabilitation robot. Table 5-6 lists these attributes with the associated percentage of respondents who identified the attribute as being #1 (most important) to #5 (fifth important). Not all respondents wrote in answers for the top five attributes. The total number of respondents in this section was 218. The top five important attributes were then combined for a total percentage of those who believed those attributes were important. Cohen’s Kappa amongst four raters ranged from 0.87 to 0.91, which is considered very good agreement [27].

5.4.8 Usage and cost

A majority of respondents (93%) stated they would like to see a RRD that is able to be used both with a therapist and for personal use at home, while a few felt a robotic device should be used only with a therapist (7%). When asked about cost, many respondents felt that they (or their clinic, hospital) would pay $1000 to $5999 USD for a device (46%). Others felt that it should be below $1000 USD (28%), 11% felt it could be $6000-$9999 USD, and 4% felt they would pay from $10,000-$24,999. Two respondents (1%) were willing to pay $25,000-$50,000 and no respondents were willing to pay more than $50,000 USD. Only 9% of those surveyed were not interested in purchasing a device. Ten respondents did not respond to this question. There were no statistically significant differences when comparing therapists’ country of practice.

5.5 Discussion

If there are so many RRDs being developed, why develop another one? Clinical practice recommendations have been made for the use of robotics in upper limb stroke rehabilitation [93], [94], and yet only a very small percentage (6%) of the therapists surveyed reported having used robot-assisted therapy. This may be an indication that current RRDs are not meeting the needs of therapists.
5.5.1 Current therapy for stroke treatment and importance for design

Understanding the methods and aims of stroke treatment used by therapists to treat the upper limb is important to guide design and integration of robotic rehabilitation devices into clinical practice. Therapists using different methods or techniques may wish to have devices with certain functions, features, or assessment parameters aligned with their current practices. Incorporating the needed and preferred functions into the design may reduce learning requirements and assist with the acceptance of a new device. Differences in rehabilitation techniques would govern how the robotic rehabilitation device would control joint and muscle movement, and how feedback is given to the stroke survivor. These differences may be inferred by the sections on current treatment methods, aims of rehabilitation, managing muscle tone, sensory feedback and facilitation of movement. Responses would also govern types of interactive activities or exercises that should be programmed into the device.

5.5.1.1 Differences between countries

Some differences between therapists’ practice from country to country may be expected as different countries have different guidelines and recommendations for stroke therapy [93],[94]. Therapists’ education in different countries may stress one approach over another, which may also lead to differences in stroke therapy approaches. Where there are similarities in responses between therapists from different countries, these can be used to inform the basic upper limb RRD. Aims such as facilitating functional activities and preventing further injury or complications can be incorporated into the basic unit. Where there are differences, different modules or programs may be developed for a specific country.

Canadian therapists seem to prefer the NDT approach compared to therapists from the other countries, whereas Australian and American therapists prefer the motor relearning approach. A robotic device developed for a Canadian audience may need to work with the NDT approach, which may include joint and muscle biofeedback to ensure proper positioning as well as allowing for muscle tone management. Devices aimed at American and Australian audiences may need to incorporate motor relearning principles, for example having a device that could sense what part of an activity a user is not able to perform and assigning tasks to
the user. This feature may be also incorporated into an NDT approach as well. This may be more readily incorporated into the software development rather than the hardware development.

As robotic rehabilitation devices have the advantage of providing high intensity practice, they may also be more readily accepted in Australia or the USA as these countries currently use more high intensity or practice in their approaches and therapists from these countries tended to agree that high intensity, focused therapy would allow a stroke survivor to recover sooner.

The design of the RRD is meant to be iterative and reliant on feedback from focus groups. Accordingly, there would need to be focus groups conducted in different countries to account for different approaches in upper limb stroke rehabilitation. Providing a useful rehabilitation robot for each country may depend on the type of practice that is predominantly used in that country. Therefore country specific focus groups may need to evaluate the RRD. This would be especially true if only focus groups are conducted in Canada as Canada seemed to differ more than Australia and the US on approaches to stroke rehabilitation.

5.5.1.2 Differences between therapist occupation and therapist experience

Overall there were not many differences between therapists’ occupation and years of experience. The differences between PTs and OTs (motor relearning program, splinting/orthosis, electrical stimulation) may be due to different ways the two professions are educated and different best practices within each profession. There were only two approaches to treatment which differed when comparing therapist years of experience – motor relearning and CIMT. As the differences are few, the design of the RRD would probably not be influenced so much by the occupation of the therapist nor the number of years of practice.

5.5.2 Aims of rehabilitation and device design

From the results, the high percentage of respondents who rated facilitating functional activities as an important aim (95%) suggests that a RRD which would allow for repetitive task or functional training would be more accepted. The mechanical features of the robot would
need to allow for movements that are common to ADLs. The software programs that the device would use would need to incorporate movement involved in tasks of daily living, perhaps evaluate which parts of the task the stroke survivor is unable to do, and provide exercises for those tasks.

A pain detection system with an automatic shut-off switch to prevent further injury and prevent secondary tissue changes may aid therapists who do not know if their client is in pain or is getting too tired. Sensors could detect if a joint is out of place and stop the device, or alert the therapist/caregiver. These sensors could also aid in restoring joint alignment. EMG sensors could be used to aid in developing muscle activation awareness and eventually allow users to learn how to isolate different muscles.

It has been shown that video games can increase perceptual-motor skills in the elderly [95]. Linking a robotic rehabilitation device to a visual display as well as adding haptics may also aid stroke survivors in improving their co-ordination. Haptics would be important in gaining real feel sensory information and visuals would aid in hand-eye coordination. Haptics may also be used to help someone learn normal muscle movement through guided exercises.

The aims of rehabilitation change with different levels of impairment and with different stroke survivors, an evaluative component of a RRD may aid in assisting therapists to determine different goals for the stroke survivor. For example, one therapist indicated that compensatory strategies were a last resort. At this point, a RRD may not be necessary. However, an application not connected to an RRD could be developed to aid in reminding stroke survivors of compensatory strategies they could use.

There were not many statistically significant differences between country, occupation, and therapists’ years of experience; these differences would not affect the design with regards to aims of rehabilitation for the robotic device.

5.5.3 Managing muscle tone and sensory feedback

Muscle tone management may vary in importance for therapists, as there was poor consensus among them for most items in this section, except for ‘functional tasks may improve
without changes in tone’. This in fact may reflect different beliefs about what is important to target in treatment. Based on the survey results, controlling muscle tone may not be a high priority for therapists as the median score was ‘somewhat important’ and therefore may not be that important when developing a RRD.

For the most part, the sensory feedback section did not have strong agreement. This could have been because few therapists currently use EMG feedback (9%) or joint position feedback (12%) and so would not know about the benefits of sensory feedback. However, in the robotic rehabilitation device section, respondents strongly agreed that the device should give some kind of biofeedback to the user. More focus group and user testing would be necessary to determine whether or not biofeedback on a RRD would be necessary for therapists.

5.5.4 Facilitation of movement and device design

The top three statements for the ‘facilitation of movement’ section indicate that a robotic device would need to have task oriented activities, provide context specific cognitive activities, and provide trunk stability. Activities could provide context specific cognitive learning as well as physical practice, for example using an automated banking machine to punch in numbers (cognitive) and take cash (physical reaching activity). They could also be fun activities like playing cards, which would use both cognitive abilities and physical abilities (passing cards, putting a card in the middle, etc). If such activities were too complicated, they could be broken down into smaller parts. Trunk stability could be incorporated into a device. However, this could also be done using a separate chair or wheelchair restraining device.

Most therapists believed that stroke survivors needed regular one-on-one therapy sessions. Although a robotic device could never replace a therapist, it could be used by therapists to provide home training or allow therapists to supervise more than one patient at a time. Building a RRD could easily incorporate high intensity, repetitive active motor sequences. In addition, an actuated device could provide strength training.
5.5.5 Robotic rehabilitation device development

Given size and cost restraints in developing a robotic rehabilitation device, knowing the necessary top features and functions would aid in developing a device that is useful, yet cost effective. While there was no statistical significance, the ranking of device requirements by respondents suggested that the device to be able to: facilitate many arm movements, be usable in a seated position, give biofeedback to the user, have virtual ADL activities, be useful at home, adjust resistance based on client performance, be modular, and maintain proper joint alignment. Based on responses, development of future devices could focus on the specifics of the above requirements.

A rehabilitative robot would need to allow for task-oriented practice within an ADL context and not simply facilitate repetitive arm movements. In addition, in the comments section, respondents indicated that they did not want a device that simply moves the affected arm passively, but would require some initiation on the part of the user. One method of addressing this would be to develop task-oriented therapy that could be done in a virtual reality type environment that would require the user to initiate movement. The device could aid or even provide assistance, but users would need to initiate the movement.

All aspects of facilitating movement do not need to come from the RRD. Some aspects could from the therapist or another device. For example, most respondents (92%) agreed that ‘trunk stability is a prerequisite for quality upper arm movement’, yet only 14% rated this as a top attribute and only 63% agreed that this was a requirement. There may be a difference between actual non-robotic current practice and what respondents would desire to see in a rehabilitation robot. For example, many respondents (62%) listed biofeedback to the client as a top attribute, although it was only seen as somewhat important amongst the respondents surveyed.

Many aspects of a potential RRD would be desirable; almost all of the listed robotic requirements’ median score was either ‘strongly agree’ or ‘somewhat agree’. These requirements must be carefully balanced with cost requirements, as most respondents would purchase at a cost of below $6000 USD. The device requirement rankings gave some
indication of the top features a robotic device should have. The ranked top attribute list (Table 5-6) and the Likert agreement scale list (Table 5-5) differed in their ranking, as some respondents strongly agreed that a certain attribute is important, but may have ranked other attributes as being more important. A five-point Likert scale may have been too limited in ranking device requirements to indicate which attributes are more important than others.

A RRD would need to be adaptable to rehabilitating different types of movement for different stages of recovery as needs of stroke survivors differ. It would need to facilitate many different arm movements, which would mean at least three degrees of freedom. The device would also need to be able to adjust its resistance or assistance based on the user as well as allow users to be in different positions (seated or standing). This device should allow for different approaches to therapy. For example, both should be able to control for or allow for compensatory movements. A device that would be able to record progress may also be able to augment therapist decision making in terms of what types of therapy and strategies to use.

In developing a rehabilitative device, it cannot be based on one therapeutic approach. As much as possible, devices should allow therapist to use the different approaches of therapy therapists feel would most benefit their clients. An option would be to have modular units that specifically cater to different approaches to therapy. For those who subscribe to repetitive task training, it may be that in a clinic or hospital setting the full device is used to evaluate the client. Then certain repetitive tasks may be assigned with a robot for home use. A therapist wanting to monitor their client more closely (such as in NDT) would be able to use a biofeedback module. Approaches where alignment is not as critical, such as motor learning, could do without this module. The device could allow for different methods of practice (i.e. block versus random practice).

Different rehabilitation techniques may also be incorporated in the software programming of the device. For example, different programs based on different types of therapy could be developed. Repetitive task training would require the programs to be task specific, for example include predominantly ADLs, and not simply repetitive motions and tasks. A motor relearning program may be able to analyze which parts of a task a stroke survivor is unable to perform
and ‘assign’ specific exercises, which may be repetitive motion, to the stroke survivor. A NDT program may want to give more biofeedback to allow monitoring of spasticity and abnormal postures and movements. When abnormal movements occur, the program could aid in inhibiting those types of movements.

A majority of respondents (93%) could envision a rehabilitation device as being both for the home and a clinic or hospital. This would require that the device be compact enough to be transportable, or inexpensive enough to allow for home purchase or lease. In developing such a device, one of the goals was to increase access for stroke survivor rehabilitation. In order for the goal of better access to be obtained, a device cannot be restricted to a hospital or clinic environment.

5.5.6 Current rehabilitation robotic devices on the market

Many of the robotic rehabilitation devices currently available do meet the top criteria. However, they may not be compact or convenient enough for stroke survivors to use in the home. As 60% of respondents rated ‘be a useful tool for stroke patients to use at home’ one of the top five RRD qualities and 93% said they would desire a robotic rehabilitation device that is usable both with a therapist and for personal practice, this would indicate a strong preference for a device that can be taken home with a stroke survivor.

Since upper limb robotic rehabilitation devices are shown in studies to have similar results when compared to conventional therapy and most robotic devices on the market are quite costly, cost may be a limiting factor to therapists’ use of robotic rehabilitation devices. Clinics may be apprehensive in purchasing a device if costs are similar or more than costs of hiring a therapist. Only 5% were willing to pay between $10,000 to $50,000 USD, and most of the current devices on the market are more than $10,000 USD, with the actuated devices costing more than $50,000. It is interesting to note that 6% of the respondents had used a robotic rehabilitation device in the past. It could be that most therapists as they have not been exposed to robotic rehabilitation devices would not choose to use one unless the costs were dropped dramatically.
5.6 Limitations

5.6.1 Survey sample

The survey was first sent to professional associations and email list services, which may
have introduced a selection bias in the sample as it depended on a third party to determine
which respondents would receive the survey. In addition, anti-spam laws in certain countries
limited the survey being distributed as widely as it could have been. As online surveys have
become more popular, the response rate may have been low, as can be seen by how many
times the survey was viewed compared to the completed responses.

5.6.2 Survey construction

This survey primarily used closed responses and statements to elicit agreement/
disagreement or a ranking of importance. The way the statements were phrased, especially in
the ‘tone management’ section, may have been confusing to some and therefore would affect
their responses. In retrospect the agree/disagree scale should have been used in this section
instead of important/unimportant.

Although the survey was sent to English speaking professional organizations, there are
some words that may be interpreted differently from country to country. Consensus rates for
the survey items were above 50%, giving average to good consensus on items of the survey.

The survey was constructed through reviewing other surveys and observing and consulting
with OTs specializing in stroke rehabilitation at a rehabilitation hospital. This would have
introduced a bias to the questions, as the therapists that provided input were likely to have an
approach to stroke rehabilitation that was common practice in their country of residence, their
employment institution, and their background. The statements selected would have reflected
these types of bias and may have caused difficulties for those who use other approaches.

The survey did not give a case study or an example of a client’s level of recovery, therefore
answers would have varied in the sections ‘aims of rehabilitation’, ‘tone’, and ‘facilitation of
movement’ depending on the stroke survivor’s level of impairment or disability. For example,
several respondents on the section concerning ‘aims of rehabilitation’ commented that compensatory strategies are used when normal movements are not possible, although it is not the first option.

The ‘robotic rehabilitation device’ requirements section had respondents envision a robotic device and questions reflected this imaginary device. The answers may have been limited by the imagination of the respondents, or robotic devices they have seen in the past. In addition, forced ranking of the top attributes may have introduced unwanted error, especially as there were two separate lists for respondents to rank, which if listed differently, may have affected the rankings of each attribute.

A five-point Likert scale may not have given enough resolution to the answers. There is also the problem of acquiescence bias as most of the answers were either in agreement or would find a certain attribute as important.

5.6.3 Survey analysis

Methods of survey analysis may have introduced unwanted error. As the data were descriptively analyzed with no statistical comparison tests, it can only be read descriptively and not conclusively. Combining response levels and excluding the neutral responses on the Likert scale may have also introduced unwanted error.
Chapter 6. Preliminary Design of the Upper Limb Rehabilitation Device

This chapter introduces the preliminary design of an upper limb RRD.

Using information culled from the survey described in Chapter 5, a preliminary prototype was designed. Survey information was input into a House of Quality model to map customer requirements to technical specifications. As the initial prototype was only intended as a starting point, the targets were not rigid. User centered design is iterative, and the first iteration and prototype was designed to give therapists something to critique.

6.1.1 Quality function deployment

There are many ways to turn user requirements into concrete specifications. One method, developed in Japan to transform user requirements into design, as well as ensure the design quality is passed onto the manufacturing process, is called Quality Function Deployment [96]. This design process has been used to design consumer products, transportation, electronics, software, and services [97]. In essence, quality charts and matrices are constructed based on the customers’ requirements and comments, which are grouped into similar categories.

Customer requirements are given a number based on the relative importance of that requirement, which is based on survey results [98]. The purpose of the quality chart is to convert the customer requirements into technical specification targets. The customer requirements are given a point value based on their relationship to each technical specification. These specifications are then tallied and target specifications are set.

6.2 House of quality methodology

Results from the survey were used to inform the design of a prototype rehabilitation device. The technical requirements of the device were prioritized using the House of Quality matrix [99]. The House of Quality was first used to prioritize therapist (“customer”) requirements and link them to technical requirements to determine the design criteria. See Appendix C for more details on the House of Quality.
Customer requirements were derived from the survey, using percentages of respondents’ agreement with statements or perceived importance of desired features. These percentages were scaled up by a factor of ten to assign a weight to each requirement. In addition, written comments that pertained to the design of the device, were included in the customer requirements, although not surveyed, they were given an arbitrary value of ‘1’ for the weight. Customer requirements were put on an affinity chart and grouped according to similar characteristics.

Technical requirements were created in consultation with the industrial partner, Quanser Consulting (Markham, ON, Canada; www.quanser.com). These requirements of a RRD were put in an interaction matrix, indicating which requirements have negative or positive correlations with each other, see Figure 6-1.

The planning matrix was not done with competitors’ products as only 6% of therapists surveyed had used robotic rehabilitation therapy. What was used instead was the foreseen prototype and how this prototype would be able to meet customer requirements. The foreseen prototype was constrained by cost constraints from the survey (less than $6000) and manufacturing constraints set by Quanser. A mark from zero to five was given to each customer requirement. This was multiplied by the customer requirement weight to give an overall weight to each requirement.

Technical priorities were calculated with an interrelationship matrix of the technical specifications and the customer requirements, with a ‘3’ indicating strong correlation, ‘2’ medium correlation, and a ‘1’ weak correlation, if there was no correlation, no number was assigned. These numbers were selected arbitrarily to get a general sense of importance. These numbers were then multiplied by the overall weight from the planning matrix and summed for each technical requirement.

Target priorities were calculated as the sum of the total points for technical priorities and as a percentage of the total priorities. Targets were then generated using the 95th percentile of anthropometric data [100], [101], normal values for ROM, values for strength in rehabilitation [102], portability with regards to airplane carry on sizes and safe lifting standards
[103], [104]. Assistive forces were calculated using acceleration data from stroke affected and non stroke affected persons moving typical objects from an ADL activity, a glass and a plate [105], then multiplied by the 95th percentile of the mass of the arm taken from anthropometric data [106]. Resistive forces were calculated using the 95th percentile mass of the arm and movement against gravity [102]. Resolution requirements (how sensitive to small movements) were taken from the HapticMaster, a haptic robotic device [107]. Numbers of links and joints were calculated using a two DoF model in order to decrease costs. Compatibility issues were addressed using current standards in Canada.

6.3 House of quality results

The house of quality shown in this thesis has been broken up to fit into the thesis. See Appendix C for an overall view of the house of quality.

6.3.1 Customer requirements

Categories of customer requirements were determined using an affinity chart. Five main categories were assigned: quality of rehabilitation, usability, accessibility, safety, and motivational factors. Quality of rehabilitation was further broken down into movement patterns, degrees of freedom, speed, ability to assist or resist, and feedback. Usability was broken down into patient interface, therapist interface, and general control interfaces. Motivating factors (Motivate) were further broken down into ADL activities and fun activities. Table 6-1 and Table 6-2 show the grouped customer requirements as well as the planning matrix used. Table 6-1 and 6-2 show the customer requirements grouped in their categories and subcategories.
Table 6-1. Scoring of customer requirements and planning matrix
Survey results (% in agreement, % indicating importance), Weight=survey results x 10, planning score based on manufacturing and cost capabilities. Overall weight = Planned x Weight

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Survey %Agree/ %Important</th>
<th>Weight (10 high)</th>
<th>Planned (5 high)</th>
<th>Overall Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quality Rehabilitation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement Patterns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improves coordination</td>
<td>91%</td>
<td>9.1</td>
<td>5</td>
<td>45.50</td>
</tr>
<tr>
<td>Learn normal muscle movement</td>
<td>87%</td>
<td>8.7</td>
<td>4</td>
<td>34.80</td>
</tr>
<tr>
<td>Compensational strategies</td>
<td>53%</td>
<td>5.3</td>
<td>1</td>
<td>5.30</td>
</tr>
<tr>
<td>Few high quality movements better than many poor quality</td>
<td>63%</td>
<td>6.3</td>
<td>3</td>
<td>18.90</td>
</tr>
<tr>
<td>Functional Activities</td>
<td>95%</td>
<td>9.5</td>
<td>5</td>
<td>47.50</td>
</tr>
<tr>
<td>Bilateral movements</td>
<td>79%</td>
<td>7.9</td>
<td>2</td>
<td>15.80</td>
</tr>
<tr>
<td>DoF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facilitate many arm movements</td>
<td>93%</td>
<td>9.3</td>
<td>4</td>
<td>37.20</td>
</tr>
<tr>
<td>Transverse plane</td>
<td>94%</td>
<td>9.4</td>
<td>5</td>
<td>47.00</td>
</tr>
<tr>
<td>Sagittal plane</td>
<td>95%</td>
<td>9.5</td>
<td>5</td>
<td>47.50</td>
</tr>
<tr>
<td>Slow movement</td>
<td>52%</td>
<td>5.2</td>
<td>5</td>
<td>26.00</td>
</tr>
<tr>
<td>Movement graded</td>
<td>70%</td>
<td>7.0</td>
<td>3</td>
<td>21.00</td>
</tr>
<tr>
<td>Resists or assists (not passive)</td>
<td>0%</td>
<td>1.0</td>
<td>5</td>
<td>5.00</td>
</tr>
<tr>
<td>Strength training</td>
<td>85%</td>
<td>8.5</td>
<td>3</td>
<td>25.50</td>
</tr>
<tr>
<td>Resistance based on user performance</td>
<td>96%</td>
<td>9.6</td>
<td>5</td>
<td>48.00</td>
</tr>
<tr>
<td>Feedback</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keeps track of progress/improvements</td>
<td>0%</td>
<td>1.0</td>
<td>5</td>
<td>5.00</td>
</tr>
<tr>
<td>Biofeedback (client)</td>
<td>90%</td>
<td>9.0</td>
<td>3</td>
<td>27.00</td>
</tr>
<tr>
<td>Biofeedback (Therapist)</td>
<td>81%</td>
<td>8.1</td>
<td>3</td>
<td>24.30</td>
</tr>
<tr>
<td>Vision rehab in activities</td>
<td>0%</td>
<td>1.0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Maintain joint alignment</td>
<td>95%</td>
<td>9.5</td>
<td>3</td>
<td>28.50</td>
</tr>
<tr>
<td>Pain management</td>
<td>0%</td>
<td>1.0</td>
<td>3</td>
<td>3.00</td>
</tr>
<tr>
<td>Audible cues to orientate</td>
<td>0%</td>
<td>1.0</td>
<td>2</td>
<td>2.00</td>
</tr>
<tr>
<td>Usability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Separate interfaces</td>
<td>69%</td>
<td>6.9</td>
<td>3</td>
<td>20.70</td>
</tr>
<tr>
<td>Predefined buttons</td>
<td>55%</td>
<td>5.5</td>
<td>3</td>
<td>16.50</td>
</tr>
<tr>
<td>Touch screen</td>
<td>54%</td>
<td>5.4</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Voice activated- VR link</td>
<td></td>
<td>1.0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Control Interface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact points for therapist</td>
<td></td>
<td>1.0</td>
<td>5</td>
<td>5.00</td>
</tr>
<tr>
<td>Little adjustment from therapist after deployed</td>
<td>79%</td>
<td>7.9</td>
<td>5</td>
<td>39.50</td>
</tr>
<tr>
<td>Easily cleaned</td>
<td></td>
<td>1.0</td>
<td>5</td>
<td>5.00</td>
</tr>
<tr>
<td>Therapist Interface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No tools required</td>
<td></td>
<td>1.0</td>
<td>2</td>
<td>2.00</td>
</tr>
</tbody>
</table>
Table 6-2. Scoring of customer requirements and planning matrix
Continued from Table 6-1. Survey results (% in agreement, % indicating importance), Weight=survey results x 10, planning score based on manufacturing and cost capabilities. Overall weight = Planned x Weight

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Survey %Agree/ %Important</th>
<th>Weight (10 high)</th>
<th>Planned (5 high)</th>
<th>Overall Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Usability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS Interface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Require specific adjustments for good fit</td>
<td>76%</td>
<td>7.6</td>
<td>5</td>
<td>38.0</td>
</tr>
<tr>
<td>Moveable handhold</td>
<td>69%</td>
<td>6.9</td>
<td>4</td>
<td>27.6</td>
</tr>
<tr>
<td>Flexible handhold/large buttons/handhold</td>
<td>90%</td>
<td>9.0</td>
<td>4</td>
<td>36.0</td>
</tr>
<tr>
<td>Allows hand to be free</td>
<td></td>
<td>1.0</td>
<td>3</td>
<td>3.0</td>
</tr>
<tr>
<td>Seated position</td>
<td>99%</td>
<td>9.9</td>
<td>5</td>
<td>49.5</td>
</tr>
<tr>
<td>Standing position</td>
<td>94%</td>
<td>9.4</td>
<td>5</td>
<td>47.0</td>
</tr>
<tr>
<td>Recumbent position</td>
<td>63%</td>
<td>6.3</td>
<td>3</td>
<td>18.9</td>
</tr>
<tr>
<td>Exoskeleton</td>
<td>69%</td>
<td>6.9</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Accessibility</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Different handholds</td>
<td>97%</td>
<td>9.7</td>
<td>5</td>
<td>48.5</td>
</tr>
<tr>
<td>High intensity focused therapy</td>
<td>85%</td>
<td>8.5</td>
<td>5</td>
<td>42.5</td>
</tr>
<tr>
<td>Clinic &amp; Home use</td>
<td>88%</td>
<td>8.8</td>
<td>5</td>
<td>44.0</td>
</tr>
<tr>
<td>Compact</td>
<td>91%</td>
<td>9.1</td>
<td>5</td>
<td>45.5</td>
</tr>
<tr>
<td>Low Cost (&lt;$10,000USD)</td>
<td>87%</td>
<td>8.7</td>
<td>5</td>
<td>43.5</td>
</tr>
<tr>
<td>Easy to use - doesn’t require a lot of training</td>
<td></td>
<td>1.0</td>
<td>5</td>
<td>5.0</td>
</tr>
<tr>
<td>Transportable</td>
<td>91%</td>
<td>9.1</td>
<td>5</td>
<td>45.5</td>
</tr>
<tr>
<td>Modular</td>
<td>93%</td>
<td>9.3</td>
<td>5</td>
<td>46.5</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prevents secondary tissue changes</td>
<td>90%</td>
<td>9.0</td>
<td>4</td>
<td>36.0</td>
</tr>
<tr>
<td>Prevents further injury and complications</td>
<td>93%</td>
<td>9.3</td>
<td>4</td>
<td>37.2</td>
</tr>
<tr>
<td>Tamper proof</td>
<td></td>
<td>1.0</td>
<td>4</td>
<td>4.0</td>
</tr>
<tr>
<td>Arm Stability</td>
<td>87%</td>
<td>8.7</td>
<td>3</td>
<td>26.1</td>
</tr>
<tr>
<td>Trunk Stability</td>
<td>63%</td>
<td>6.3</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Hand Stability</td>
<td>86%</td>
<td>8.6</td>
<td>3</td>
<td>25.8</td>
</tr>
<tr>
<td><strong>Motivate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADL Task oriented -ADL specific</td>
<td>94%</td>
<td>9.4</td>
<td>5</td>
<td>47.0</td>
</tr>
<tr>
<td>Active motor sequences with clear functional goal</td>
<td>92%</td>
<td>9.2</td>
<td>5</td>
<td>46.0</td>
</tr>
<tr>
<td>Fun Fun activities</td>
<td>92%</td>
<td>9.2</td>
<td>5</td>
<td>46.0</td>
</tr>
</tbody>
</table>

6.3.2 Technical Requirements

The technical requirements and the correlation matrix can be seen in Figure 6-1. There were six main categories of technical requirements – workspace/ROM, motor force, size,
manipulator, technical details, and safety. They were evaluated against each other to see which requirements had positive interactions and which had negative ones. The positive interactions were marked with a ‘++’ indicating strong positive interaction or a ‘+’ indicating moderate positive interaction. The negative correlations were similarly marked with ‘--’ or ‘-’ indicating strong or moderate negative interaction. Arrows were given to each requirement to indicate the direction (increase or decrease) the specification needed to go in for a better device.

Figure 6-1. Technical requirements and interaction matrix.

 numRows = beneficial if requirement increased, numRows = beneficial if requirement decreased, ++ strong positive interaction, + positive interaction, -- strong negative interaction, - negative interaction
### Table 6-3. Interrelation matrix of customer requirements and technical requirements

3=high correlation, 2=medium correlation, 1=low correlation, blank=no correlation

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Frontal Axis</th>
<th>Saggital Axis</th>
<th>Longitudinal Axis</th>
<th>Yaw</th>
<th>Pitch</th>
<th>Roll</th>
<th>Resisive</th>
<th>Assistive</th>
<th>Acceleration</th>
<th>Resolution</th>
<th>Length</th>
<th>Width</th>
<th>Height</th>
<th>Weight</th>
<th>Units</th>
<th>Joints</th>
<th>End Effector</th>
<th>Power Reg’s</th>
<th>Sensors</th>
<th>Actuator</th>
<th>Compatibility</th>
<th>Meets standards</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improves coordination</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
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<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Learn normal muscle movement</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
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<td>3</td>
</tr>
<tr>
<td>Compensational strategies</td>
<td>2</td>
<td></td>
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<tr>
<td>Few high quality movements better than many poor quality</td>
<td>3</td>
<td></td>
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</tr>
<tr>
<td>Functional Activities</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Bilateral movements</td>
<td>3</td>
<td>3</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Facilitate many arm movements</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<td>3</td>
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<td>3</td>
<td>3</td>
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<td>3</td>
</tr>
<tr>
<td>Transverse plane</td>
<td>3</td>
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<td>Saggital plane</td>
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<tr>
<td>Slow movement</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Movement graded</td>
<td>3</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Resists or assists (not passive)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<td>3</td>
<td>3</td>
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<td>Easy to use - doesn't require a lot of training</td>
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</table>
Table 6-3 shows the interrelation matrix between the customer requirements and technical requirements. As many customer requirements did not neatly fit into any of the technical requirements, these spaces were left blank. However, they were taken into consideration when the device was being designed.

6.4 Targets

Technical requirement targets were calculated as a starting point for the device design. Scores from the interrelation matrix (Table 6-3) were multiplied by the overall weight of each customer requirement and then tallied to give the technical priority number. The percentage of the technical priority out of the total sum of technical priority numbers was calculated to easily compare the importance of each technical requirement, see Table 6-4.

Table 6-4. Technical targets with calculated technical priority score

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<tr>
<th>Technical Priorities</th>
<th>% of Total</th>
<th>Targets</th>
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<tbody>
<tr>
<td>Frontal axis</td>
<td>636</td>
<td>673 mm</td>
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<tr>
<td>Sagittal Axis</td>
<td>638</td>
<td>293 mm</td>
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<tr>
<td>Longitudinal Axis</td>
<td>499</td>
<td>1104 mm</td>
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<tr>
<td>Yaw</td>
<td>499</td>
<td>90 deg</td>
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<tr>
<td>Pitch</td>
<td>495</td>
<td>160 deg</td>
</tr>
<tr>
<td>Roll</td>
<td>331</td>
<td>190 deg</td>
</tr>
<tr>
<td>Resistive</td>
<td>85</td>
<td>40.6 N</td>
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<tr>
<td>Assistive</td>
<td>225</td>
<td>16.6 N</td>
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<tr>
<td>Acceleration</td>
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<td>4 m/s²</td>
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<tr>
<td>Resolution</td>
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<td>0.012mm/ct</td>
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<td>Length</td>
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<td>Height</td>
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<td>Weight</td>
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<td>550 mm</td>
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<td>Links</td>
<td>745</td>
<td>10 kg</td>
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<tr>
<td>Compatibility</td>
<td>393</td>
<td>DC</td>
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<td>Meets standards</td>
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<td>No tipping</td>
<td>12</td>
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6.4.1 Workspace and range of motion

In the calculations, these equations (6-1) assume that the person is sitting a forearm’s length from the table, see Figure 6-2. For more detailed calculations see Appendix D.

\[
x^2 + y'^2 = (x + y)^2
\]

\[
y' = y + s
\]

\[
s = \pm \sqrt{y'^2 + 2xy - y}
\]
Using data from the 95th percentile of US men (taken from two sets of data, one from civilians and one from the U.S. Marine Corps) [100], [101], where x is the shoulder-elbow length (431 mm)[100] and y is the forearm length, that is the elbow to fingertip length minus the hand length (520.4mm-209.2 mm=311.2mm) [101]. Using equation (6-1), the sagittal axis (s) workspace would be 293 mm.

For the frontal axis (f), using normal shoulder adduction/abduction (0-90°) ROM [102] while maintaining the hand on the table workspace, see Figure 6-5 and equation (6-2). The calculated frontal workspace would be 673 mm:

![Figure 6-2. Sagittal workspace for a forward reaching motion.](image)

![Figure 6-3. Frontal axis workspace requirement.](image)
The longitudinal axis would account for the flexion of the shoulder (0-90°) ROM [102]. The longitudinal maximum would be 1104 mm, see figure 6-6 and equation (6-3).

\[
f = \sqrt{(x + y)^2 - y^2}
\]

Rotational movement would be limited to the end effector for the two DoF robot, as such it would be limited to the wrist and elbow movement. Pitch movement would include wrist flexion (0-90°) and extension (0-70°), for a total of 160°. Yaw movement would include wrist abduction (0-25°) and adduction (0-65°), for a total of 90°. Roll movement would include elbow supination (0-90°) and pronation (0-90°), for a total of 180° [102]. However these end effectors were not incorporated into the first prototype.

### 6.4.2 Motor force

According to the Merck manual, the top grade of muscle strength is defined as “Full ROM against gravity and full resistance for patient’s size, age, and sex.” [102]. Thus gravity against the mass of the arm was used to calculate the maximum resistive force needed, see equation (6-4), where \(F\) is force, \(m\) is mass, and \(a\) is acceleration. The average weight of an arm was 3.216±0.464 kg [106], therefore the 95th percentile arm would weigh 4.14 kg. The acceleration from gravity used was 9.8 \(m/s^2\) [108].

![Figure 6-4. Longitudinal axis workspace requirement](image)
For assistive forces, the maximum acceleration to move a glass and plate was used, as this was a common ADL and a typical acceleration that could be used. The maximum acceleration used by subjects was determined to be $4 \text{ m/s}^2$ [105], the highest acceleration given in the study of subjects moving a glass and plate. Therefore the assistive force required would be 16.6 N.

Resolution was taken from the HapticMaster specification, a haptic device which had been used in rehabilitation (see Chapter 3). Resolution for the HapticMaster was 0.004 to 0.012 mm/count, which indicates that the system was able to detect differences as small as 0.012 mm [107].

### 6.4.3 Size

Results from the survey indicated that therapists wanted the new robotic system to be able to be portable, as there are many definitions of ‘portable’, a “carry-on” suitcase was used to determine the size restrictions as a starting point. People who have been unaffected by stroke are generally able to carry this size. The recommended maximum for 99% of women is 15 kg (more for men) in ideal circumstances. In non ideal circumstances, the maximum force is 130N for 90% of women (ISO standard 11228 Part 1 & 2 as referenced in Manuel E). The Air Canada maximum carry on size [104] was used to determine the size restrictions:

- **Length:** 400 mm
- **Height:** 550 mm
- **Width:** 230 mm
- **Weight:** 10 kg

### 6.4.4 End effector

There are different stroke survivor needs; the end effector should be modular and designed closely with the therapists. Two end effectors were designed to give therapists an idea of what may be possible. The one designed previously as a hemisphere had been used on
a previously designed prototype [18] (Figure 6-7 shows this end effector at the end of a link), another one was designed as an arm support end effector (Figure 6-7 shows this end effector on top of the device). A third was designed as a cone-shaped handle (see Figure 6-5).

6.5 Prototype design

The prototype was designed in consultation with Quanser. Many parts were previously used by Quanser in their haptic devices, but were verified by the author as to suitability for this device. The prototype was designed using SolidWorks 2010 (www.solidworks.com), see Figure 6-5.

6.5.1 Mechanical components

In designing the mechanical portion of the robotic device, previous RRDs as well as other haptic devices were examined. Therapists surveyed wanted a device to facilitate many types of movement, requiring more DoF. However they indicated they wanted a low cost device. As there have been successful two DoF device in the literature (see Chapter 3), it was determined that two DoF would be a good starting point.

A two DoF haptic device required at least two motors, one for each DoF. The maximum force required was 40.6N from the target calculations. When this was divided in half (as there were two motors), there was 20.3 N of force per motor. Smaller motors would decrease the cost of the device, but would need some type of leverage to increase the amount of force. A capstan was found to be a good option. The capstan size that Quanser Consulting used in some of their haptic devices was 10 mm in diameter. The motor that had used before was the Faulhaber 3863-048C, which was rated for 110 mN·m of continuous force and had a relatively low inertia and low friction, which would be good for haptic devices. Maximum force is four times that of continuous force so the maximum force would be rated 440 mN·m for these motors.
Two link lengths of 250 mm would allow for a reasonable sized workspace, with a maximum workspace of 1016 mm (frontal axis) x 298 mm (sagittal axis), and a “sweet spot”, where the manipulator was able to move anywhere in a central area, of 457 mm x 254 mm. The workspace looked like a crescent moon shape (Figure 6-6).
The amounts of torque were calculated with the links perpendicular to the forces (home position). Equation (6-5) shows the torque ($\tau$) equation, relating force ($F$) and the link length ($r$).

$$\tau = F \times r$$

Equation (6-5)

$$\tau = 20.3N \times 0.25m = 5.075 Nm$$

The gear ratio (equation (6-6)) would need to be 11.5, in other words, the capstan way would need to be 11.5 times the size of the capstan. As the capstan is 10 mm, the capstan way would need to be at least 115 mm. A previous capstan that had been used by Quanser was 300 mm. This would give it more than enough force while maintaining a small enough footprint. It was determined that more force would be better to test with therapists, as therapists could always test a smaller percentage of the force but could not test a larger force on a less powerful device. If less force is necessary, the workspace could increase and the size of the device could decrease. The continuous force capability for the 300 mm capstan way at the home position was 13.2 N per plane of motion and the maximum force capability was 52.8 N per plane of motion.

The gear ratio (equation (6-6))

$$\text{Gear ratio} = \frac{\tau_{\text{required}}}{\tau_{\text{motor}}}$$

$$\text{Gear ratio} = \frac{5.075 Nm}{.440 Nm} = 11.5$$

The end effector piece could be detached and replaced with different handholds depending on the needs of the user. Two end effectors were designed as something to work with for the focus groups. The handhold could be designed to allow for more degrees of rotational freedom, or a handhold that would support the forearm if the user was not able to grasp sufficiently.

A handle was placed on the device to allow it to be more easily moved, as well as a clip for the end effector. A ball caster was added for safety reasons – so the device would not tip while it was being used. In addition weather stripping around the opening of the device was necessary to help prevent objects such as hair and fingers from being caught inside the device.
The device could produce quite a bit of force, which would need to be taken into consideration in terms of slippage. The device could slip and so it would require some sort of clamping or traction to maintain its position. Rubber feet on the bottom of the device would aid in traction. The normal force for the device (at 7.5 kg) would be 73.5 N due to gravity. The static coefficient of friction (μ) for rubber ranges from 0.6 to 0.85 on a concrete surface (ref). The maximum force the two motors would produce would be 105.6 N, which would mean the force of friction \( F_{\text{friction}} \) (equation (6-7)) must counter the force from the motors or there must be a clamp which can stabilize the device. The normal force \( F_{\text{normal}} \) would range from 124 N to 176 N, which would mean that without a clamp, the device would need to be 12.7 kg to 18 kg. At 7.5 N, the device would slip, unless it was clamped down to the table. Therefore an external clamp or weights would be required (not shown).

\[
F_{\text{friction}} = \mu \times F_{\text{normal}} \tag{6-7}
\]

### 6.5.2 Electrical components

Determining basic electrical controls of the device was based on what would best suit a haptic device that would be safe to use with the stroke population. Current is proportional to the amount of torque and voltage is proportional to the angular velocity. As force was more important to control in this instance, the device would need to be current controlled rather than voltage controlled. Additionally haptic devices can be either admittance controlled or impedance controlled [70]. Impedance controlled devices input displacement and output force. With admittance control, the device inputs force and outputs displacement. The advantages of an impedance controlled device are low inertia, low cost, stability on physical surfaces, and backdrivability. Unlike industrial robotic devices, therapeutic robotic devices do not need to have precise position, but they do need to be safe and allow for backdrivable motion. It was therefore decided that the device would be impedance controlled.

Two optical encoders were needed to detect the position of the end effector; one for each motor. The encoders chosen were US Digital QD145, which were capable of detecting 4000 counts per revolution. Dividing by the gear ratio and multiplying by the link length, the
resolution was calculated to be 0.0131 mm/count or 76 counts per mm. In essence, the device was able to detect a 0.0131 mm change. Although this was larger than the target, it was still within a reasonable range.

The power supply used in the design was a Powergate Meanwell PPS125-24 with a voltage output of 24V at 5.2A. The motor required 48 V, so using two power supplies would provide enough power. The maximum power output of the power supply would be 124.8 W as calculated in equation (6-5), where \( P = \text{power}, I = \text{current}, V = \text{voltage} \). Heat sinks were needed to ensure the device would remain cool. Wakefield Engineering’s 641K was chosen as it was readily available. It has a forced convection cooling of 0.9°C/W at 250 LFM. It would be able to cool by 112°C and two of these would be more than adequate. See equation (6-9), where \( T = \text{temperature}, P = \text{power}, R_T = \text{Cooling rate} \).

\[
P = IV = 5.2A \times 24V = 124.8W \tag{6-8}
\]

\[
T = PR_T = 124.8W \times 0.9°C/W = 112°C \tag{6-9}
\]

A fan would be required to maintain an air flow of 250 LFM. The NMB-MAT 3108NL has a maximum airflow of 26.5 CFM (304 LFM) which is adequate. An AC receptacle (Corcom 6VM1S) was chosen that was rated higher (720 W) than the power needed for two power supplies (250 W). Fuses were incorporated for safety reasons. A tethered emergency stop was also added to allow therapists to stop the device in case there was a problem.

Quanser’s Q8 Industrial USB (Q8) was a hardware in the loop (HIL) board that was used to control the robot. The Q8 was able to handle eight analog and encoder inputs, eight analogy outputs, and thirty-two digital inputs and outputs. It was able to give real time control performance, which would be necessary in using a haptic robotic device.

Biofeedback sensors (EMG, joint, pain sensors) would be a separate module that could be used in conjunction with the rehabilitation device. These were developed separately and were not part of this design iteration.

The dimensions of the designed prototype were 457mm x 305 mm x 203 mm, altogether weighing approximately 7.5 kg. The device would be usable in three positions: horizontal,
lateral, and vertical. Two of these devices used together could be used as a bilateral trainer. The material cost was around $4000 CAD. The retail cost of the prototype was approximately $15,000 CAD as quoted by Quanser[109].

6.6 Design discussion

Designing a device which would meet user requirements, and yet be cost effective was a challenge. Important ways this device could be differentiated from other devices being developed could be in lower cost, more portability, and better haptic capabilities. From the survey, performing functional activities was important, as well as allowing the device to be compact and portable enough to be used at home.

6.6.1 Cost considerations

Therapists wanted a lower cost device, so cost reduction strategies were needed. There were several factors that could reduce the cost of a haptic device. These included fewer DoF, less power, fewer specialized parts, a smaller workspace, reusing parts from other products, and mass production.

Originally the device had many more degrees of freedom, but in consultation with Quanser, it was agreed that a simpler device was needed due to cost constraints. Every degree of freedom would increase material costs by $2000 according to Quanser [109]. In order to keep costs down, a modular unit with two DoF unit was proposed. Separate modules could be sold with the unit depending on user needs, for example a separate biofeedback unit and separate handholds which could accommodate different users on the machine.

The device as designed had more power than was needed, this was due to using parts that Quanser had already used (fewer specialized parts), and therefore it was considered more cost effective for this first prototype. In addition, it was thought that decreasing power would be easier than increasing the power of the device. As the device was to be evaluated by focus groups and tested, the actual power necessary could be determined. As power is decreased, either size can be decreased or workspace can be increased, both potentially good for the end
user. In addition, decreasing the power would also decrease the potential for the device to slip.

An end effector unit (as opposed to an exoskeleton) was chosen to allow therapists to have more interaction with their client as keep costs contained. End effector type devices potentially could allow for different types of therapy to be performed on the stroke survivor. Although this would be difficult when the device is taken home, physical contact with the client may allow therapists to feel more comfortable with the device, as well as a check that the device is performing as it should.

6.6.2 Portability

Therapists desired a device that would be compact and usable in either clinic or home. In order to increase portability, and therefore accessibility to rehabilitation, a desktop model was proposed. The desktop model would allow for different positions depending how it was positioned. This would increase the capabilities of a two DoF device as it could be used in different positions. It could also be used in seated, standing, and even recumbent positions. The device as designed requires a clamp, which would make it less portable and capable of adjusting to different tables.

6.6.3 Haptic capabilities

The motors and optical sensors on the device allow it to create haptic feedback, which along with visual and audio feedback would allow for more sensory and proprioceptive rehabilitation, as well as be more realistic for exercises involving ADLs. It would allow assistance and could be programmed to only assist when the user initiates movement. Haptic feedback would also be able to give resistance based on user performance.

6.6.4 End effectors

As end effectors are an important part of the design, they must be designed in conjunction with therapists to determine the types, sizes, and shapes of end effectors necessary. Further
focus groups are necessary to refine this portion of the design. Only two end effectors were designed as starting points for therapists to discuss other possibilities.

6.7 Design changes during manufacturing

While the device was being manufactured, engineers at Quanser made some modifications to the original design. It was deemed unsafe for the electrical components and mechanical components to reside in the same housing. Therefore the electrical components were encased in a separate housing with wires to connect the mechanical device to the electrical device. In addition, creating the designed capstan way was found to be too costly and therefore the capstan way was modified so that it was less hollowed out. The links were not made from a tubular shape, but were more rectangular, see Figure 6-7. The manufactured device had an increased footprint and weight as a result. The weight of the device was 17.3 kg, which allows it to be used without a clamp on most surfaces as the force of friction could potentially stabilize the device. Additional fuses were added for safety and four smaller power modules were used rather than the two larger modules proposed. As there were two separately housed parts, a motor cable and a sensor cable were necessary. The case was also redesigned by Quanser to fit just the mechanical components and another case was taken “off the shelf” for the electrical components. A summary of the target, designed and manufactured specifications may be found in Table 6-5.

As the author did not have much control over the manufacturing, this would be a limitation to the design process.
Figure 6-7. Manufactured RRD prototype, with modifications
<table>
<thead>
<tr>
<th>Specification</th>
<th>Target</th>
<th>Designed</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial/lateral axis</td>
<td>673 mm</td>
<td>762 mm</td>
<td>931 mm</td>
</tr>
<tr>
<td>Anterior/Posterior Axis</td>
<td>293 mm</td>
<td>298 mm</td>
<td>350 mm</td>
</tr>
<tr>
<td>Superior/Inferior Axis</td>
<td>1104 mm</td>
<td>1016 mm</td>
<td>931 mm</td>
</tr>
<tr>
<td>Resistive force</td>
<td>40.6 N</td>
<td>52.8 N/plane</td>
<td>52.8 N/plane</td>
</tr>
<tr>
<td>Assistive force</td>
<td>16.6 N</td>
<td>52.8 N/plane</td>
<td>52.8 N/plane</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.012 mm/ct</td>
<td>0.013 mm/ct</td>
<td>0.013 mm/ct</td>
</tr>
<tr>
<td>Length</td>
<td>400 mm</td>
<td>305 mm</td>
<td>320 mm + 180 mm</td>
</tr>
<tr>
<td>Width</td>
<td>230 mm</td>
<td>203 mm</td>
<td>140 mm + 155 mm</td>
</tr>
<tr>
<td>Height</td>
<td>550 mm</td>
<td>457 mm</td>
<td>390 mm + 305 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>10 kg</td>
<td>7.5 kg</td>
<td>17.3 kg</td>
</tr>
<tr>
<td>Links</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Joints</td>
<td>3-4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>End effectors</td>
<td>Modular</td>
<td>2 end effectors</td>
<td>2 end effectors</td>
</tr>
<tr>
<td>Power</td>
<td>AC</td>
<td>AC</td>
<td>AC</td>
</tr>
<tr>
<td>Sensors</td>
<td>Haptic, joint, pain</td>
<td>Haptic – optical</td>
<td>Haptic-optical</td>
</tr>
<tr>
<td>Actuators</td>
<td>DC motors</td>
<td>DC motors</td>
<td>DC motors</td>
</tr>
<tr>
<td>Compatibility</td>
<td>USB</td>
<td>USB</td>
<td>USB</td>
</tr>
<tr>
<td>Standards</td>
<td>CAN/CSA</td>
<td>n/a</td>
<td>CAN/CSA</td>
</tr>
<tr>
<td>Cost</td>
<td>&lt; $6000</td>
<td>$4000 material</td>
<td>$15,000 (retail)</td>
</tr>
</tbody>
</table>
Chapter 7. Prototype Risk Assessment

This chapter describes a risk assessment performed on the prototype. This assessment for the manufactured prototype was conducted to ensure user safety and awareness of risk before and while using the device. The risk assessment covered the mechanical and electrical components of the device. It did not cover the personal computer used with the device as a personal computer was considered a widely used commercial product. The assessment was completed following the National Standard of Canada CAN/CSA-ISO 14971:07 (ISO 14971:2007) Medical devices — Application of risk management to medical devices [110].

7.1 Qualitative and quantitative characteristics of the device

The intended use of the device was to aid in the therapy of the affected upper limb of individuals who have suffered a stroke. It was intended to aid in improving the ROM, developing coordination, and strengthening the affected upper limb through repetitive motion activities. In addition, it could be used to aid in the quantitative diagnostics of the upper limb with respect to ROM, coordination, and strength with a qualified stroke therapist. It was to be used in conjunction with software programs designed especially for the device. The device was intended to give haptic feedback to the user through impedance controlled motors. The end effector was able to either assist or resist the user depending on the mode selected.

7.1.1 Materials, components and device description

The upper limb stroke RRD consisted of three main components: The mechanical components, the electrical components, and computer components. The mechanical components consisted of: a casing which housed an aluminum capstan with two DC motors and two optical encoders. The internal motors were connected to two aluminum drive arms which were in turn connected to an aluminum passive arm, and an aluminum outer arm. The outer arm was then connected to a plastic end-effector on a caster wheel. The end effector could be interchanged with other end effectors. The mechanical part had rubber feet on the bottom which was to aid in preventing the case from slipping. In addition a clamp should be put on the device to add stability.
The electrical components consisted of: steel electronics casing which housed two heat sinks, a fan, three fuses, three circuit boards, and four power modules. There was one LED light on the electronics casing, indicating power on the device. An external emergency stop connected to the device through a cable, which would be used to shut off power for safety purposes. The mechanical components were connected to the electrical components through a motor cable and a sensor cable. The electrical components were then connected to a computer via a USB cable, and to an AC power source via a standard power plug.

An IBM compatible PC would be running the software that would control the device (driver software) and the rehabilitation programs (user applications software). The computer would be operated by an experienced attendant during the prototype phase. If there was a disconnection between the device and the software the device would not operate. If there was a disconnection between the driver and the device, the software would not run.

7.2 Intended use

Intended end users included stroke survivors who needed upper limb rehabilitation in conjunction with stroke therapists or caregivers of stroke survivors. A skilled attendant would be present at all times to provide instructions for use, set up programs and stop the device in case of emergency. The device was intended to be in contact with patients’ upper limb – either the hand or the forearm. It was not a single user device and may be used for more than one individual. A therapist or caregiver would be in contact with cables and wires that attach the device to a computer and to a power source.

The therapist or caregiver would use the computer to set up the required rehabilitation program. During the prototype phase an experienced attendant would be operating the software. The attendant was able to control the device’s modes. Before the device arm could be activated the attendant must calibrate the workspace. The user who required rehabilitation would grasp the end effector or place their hand/forearm in the hand rest depending on the end effector.
The device could aid movement in the same direction, resist movement, or move the user’s arm when the user was passive. The application software via a user interface allowed the attendant to set appropriate the damping gain (N s/m) or resistive force, and a spring Constant (N/m) or assistive force for the user. Maximum thresholds were set so that beyond a certain velocity or force, the power would be cut and the device arm would become limp. The device could also allow the user to feel haptic forces. The computer ran the rehabilitation program, which tracked the movement of the end effector through the optical encoders. The motors were impedance controlled, which allowed for a safer and more backdrivable device, and haptic feedback was given to the user through the drive arms, which were controlled by the motors. The driver software was set to allow a maximum input current of 1.9 Amps to the motors.

An emergency stop switch, connected by a cable to the electrical device, was placed for easy access for the attendant. Once the emergency stop was pushed, power to the motors would be cut, and the device arm would become limp. The emergency stop needed to be reset by the attendant before the device was operational again. In addition, when the rehabilitation program was stopped, the user interface window closed, or the reset box or exit box clicked on, power to the device arm would be cut, and the end effector would go limp.

The maximum workspace in the horizontal position was 931 mm x 340 mm. The continuous force capability at the home position was 13.2 N per plane of motion, and the maximum force capability was 52.8 N per plane of motion. The resolution at the home position was 0.0131 mm/count, indicating optical sensors are able to sense movement as small as 0.0131 mm.

Maintenance and calibration are necessary for optimal usage. Calibration is to be carried out before each use and would be done by a trained attendant. Day to day maintenance could be carried out by the attendant, for example cleaning the device from dust, which may interfere with optimal performance. More intensive maintenance should be carried out by a specialist, who may need to tighten the capstan wire, or repair any loose cables, which may be checked on a yearly basis. No special equipment was necessary for proper calibration. Day to
day maintenance did not require any special equipment, except for cleaning materials. More intensive maintenance would require special tools.

The lifespan of the current prototype was anticipated to be approximately one year or the length of the trials. At that point in time the device would be re-evaluated. The device was intended for indoor use in dry environments. It was not designed to be submerged or exposed to continuous flow of liquids. It was intended to be used between the temperatures of -10°C to 60°C, with a working humidity of 10-95% RH based on the power module components. The device was not life sustaining or life supporting.

The device was not sterile, nor intended to be sterilized. It was not intended to be implanted. To prevent the spread of disease and for microbiological control, the end effector would need to be cleaned and disinfected. Hand sanitizer would be made available. This process would occur between different users. Following Toronto Rehab’s institutional policy for the Sterilization and Disinfection of Equipment, V8-2001, the device would first be cleaned (the removal of foreign material, especially organic matter). As the device is classified as a non-critical item (as it ordinarily only touches intact skin and not mucous membranes), low-level disinfection would be then used (the process of killing most vegetative bacteria and some fungi and viruses, but not mycobacteria or bacterial spores). For this type of disinfection at least a 1/50 dilution of a 5.25% hypochlorite solution (bleach) would be used to wipe the patient contacting surfaces clean.

7.3 foreseeable hazards

Not every hazard is foreseeable, thus a risk assessment is an ongoing process. In evaluating the risks in using the prototype, several people were involved, including the manufacturer, the software designer, an occupational therapist, and an engineer. Tables 7-1 to 7-5 list the foreseeable risks of the device under normal and fault conditions. For each hazard, the risk was estimated by looking at the severity of the result and its probability of the risk occurrence. For each risk, measures were made to minimize the risk and a new severity rating was given after the precautions are taken. Tables 7-1 to 7-5 give the results of this risk analysis.
There are several intolerable risks, predominantly concerning the use of the device, as it may fall. It is therefore imperative that the prototype be used under close supervision until these issues can be satisfactorily resolved.

### 7.4 Hazard rating system:

Severity of an event was determined by the level of harm:

- **High** – Death or serious injury.
- **Moderate** – Long term pain, loss of function, or recoverable non-life threatening injury.
- **Low** – Minor injury, discomfort and nuisance.
- **Very low** – No injury, irritation and discomfort only.

Probability of the event occurring:

- **Frequent** – Greater than once per week.
- **Probable** – Less than once per week but greater than once per month.
- **Occasional** – Once per device over its intended life (or six months).
- **Remote** – Unlikely but may occur over the range of users.
- **Improbable** – So unlikely that it is assumed it will never occur.

Risk the resultant estimate of potential for hazardous occurrence:

- **Intolerable** – Risk must be eliminated or reduced by protective measures.
- **Undesirable** – Risk is acceptable only if it cannot be mitigated by product enhancement; warnings required.
- **Tolerable** – Risk acceptable subject to appropriate warnings.
- **Negligible** – No action necessary.
<table>
<thead>
<tr>
<th>Harm</th>
<th>Result</th>
<th>Severity</th>
<th>Probability</th>
<th>Method to Minimize Risk</th>
<th>Risk After Precaution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overheating of the electrical components</td>
<td>Fire hazard</td>
<td>High</td>
<td>Improbable</td>
<td>Allow air to circulate through the van, do not cover vent holes, as the motors will be covered by a case, heat sinks are used to dissipate heat</td>
<td>Negligible</td>
</tr>
<tr>
<td>Overheating of the motor</td>
<td>Feeling of heat, possible fire hazard</td>
<td>Moderate</td>
<td>Remote</td>
<td>Software limits motor power, space around motors to allow air circulation</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Noise from the fan</td>
<td>Slightly disturbing</td>
<td>Very Low</td>
<td>Probable</td>
<td>Fan encased in steel housing</td>
<td>Negligible</td>
</tr>
<tr>
<td>Contact with electrical components</td>
<td>Electrical shock</td>
<td>Low</td>
<td>Remote</td>
<td>Electrical components are not easily accessible. The electrical box is housed separately from the mechanical components. The wires are sealed and enclosed in the cables.</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Internal electrical short circuit</td>
<td>Smoke, fire hazard</td>
<td>Moderate</td>
<td>Remote</td>
<td>Power components are grounded and there are safety fuses installed</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Cross infection between different users of the device</td>
<td>Nosocomial infection</td>
<td>High</td>
<td>Occasional</td>
<td>The end effector will be cleaned and disinfected between each use, and hand sanitizer will be available for use before and after use</td>
<td>Tolerable</td>
</tr>
</tbody>
</table>
### Table 7-2. Environmental hazards associated with the RRD.

<table>
<thead>
<tr>
<th>Harm</th>
<th>Result</th>
<th>Severity</th>
<th>Probability</th>
<th>Method to Minimize Risk</th>
<th>Risk After Precaution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variations in external power</td>
<td>Power to the device will shut off and the device arm will go limp</td>
<td>Very Low</td>
<td>Remote</td>
<td>Connect device to surge protected outlets</td>
<td>Negligible</td>
</tr>
<tr>
<td>Tripping/pulling on the cords connecting the mechanical unit to the electrical unit, or connecting the electrical unit to the computer</td>
<td>Device could fall on the individual and be hurt</td>
<td>Moderate</td>
<td>Occasional</td>
<td>Cords will be placed in such a manner as to be out of the way of the user or others who may be passing by</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Liquids or other substances spilled on the device</td>
<td>Electrical short circuit</td>
<td>Very Low</td>
<td>Occasional</td>
<td>The electronics and mechanical motors will be encased</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Dust accumulate on the rubber feet</td>
<td>The device could slip while in use and fall on an individual</td>
<td>Moderate</td>
<td>Probable</td>
<td>Device feet will be checked for dust and clean on a regular basis. A clamp to add additional security will also secure the device</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Dust accumulate on the electrical and mechanical components</td>
<td>The device could stop functioning</td>
<td>Very low</td>
<td>Remote</td>
<td>Device will be regularly clean of dust</td>
<td>Negligible</td>
</tr>
</tbody>
</table>
Table 7-3. Hazards associated with the use of the RRD.

<table>
<thead>
<tr>
<th>Harm</th>
<th>Result</th>
<th>Severity</th>
<th>Probability</th>
<th>Method to Minimize Risk</th>
<th>Risk After Precaution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cords can be pulled out</td>
<td>No power will go to the device arm</td>
<td>Very Low</td>
<td>Probable</td>
<td>Cords can be placed in such a manner as to not interfere with normal use</td>
<td>Negligible</td>
</tr>
<tr>
<td>Computer shuts down unintentionally</td>
<td>The device arm will go limp</td>
<td>Very Low</td>
<td>Remote</td>
<td>Computer and software will be checked regularly to ensure proper function.</td>
<td>Negligible</td>
</tr>
<tr>
<td>Device may tip if the end effector and enough downward force is applied</td>
<td>The device may fall off the table and injure as it is heavy</td>
<td>Moderate</td>
<td>Probable</td>
<td>Ensure device’s and effector’s full range of motion is on a surface such as a table. Attendant will closely monitor use of device.</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Force from the motors could push the device back from the user</td>
<td>The device may fall off the table and injure as it is heavy</td>
<td>Moderate</td>
<td>Probable</td>
<td>Ensure that the controls of are set, so the device will not produce such great forces, attendant will set forces at a safe range. Physical emergency stops such as hitting the e button, pulling out any cords, or software controls will be in place.</td>
<td>Intolerable</td>
</tr>
<tr>
<td>Fingers, hair, or clothing caught in the device arm link</td>
<td>Physical harm/property damage</td>
<td>Moderate</td>
<td>Probable</td>
<td>Educate so that hands are not put near linkages or inside the device while it is operating.</td>
<td>Undesirable</td>
</tr>
<tr>
<td>Fingers, hair, or clothing caught inside the motor</td>
<td>Physical harm/property damage</td>
<td>Moderate</td>
<td>Remote</td>
<td>The motors are housed in a casing so as to prevent objects from entering the device. The motors are far from the opening of the device</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Users hand suddenly falls off the device</td>
<td>The device could hit the hand</td>
<td>Moderate</td>
<td>Probable</td>
<td>An attendant will be monitoring the activities of user and will stop the device if this event occurs.</td>
<td>Undesirable</td>
</tr>
</tbody>
</table>
Table 7-4. Hazards associated with the use of the RRD
(continued from the previous page)

<table>
<thead>
<tr>
<th>Harm</th>
<th>Result</th>
<th>Severity</th>
<th>Probability</th>
<th>Method to Minimize Risk</th>
<th>Risk After Precaution</th>
</tr>
</thead>
<tbody>
<tr>
<td>End effector impacts the user</td>
<td>Physical harm</td>
<td>Moderate</td>
<td>Probable</td>
<td>Range of motion will be adjusted on the device so that the end effector does not reach the user’s body.</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Leaning on end effector when the end effector is not on a stable surface</td>
<td>Device could tip and cause person to fall</td>
<td>Moderate</td>
<td>Probable</td>
<td>End effector will be placed so that it is always over a stable surface. Educate users not to lean on device</td>
<td>Undesirable</td>
</tr>
<tr>
<td>Operation by an unskilled person</td>
<td>System will not function as intended</td>
<td>Moderate</td>
<td>Occasional</td>
<td>Built in safety limits to prevent dangerous forces. The prototype will only be used under skilled supervision</td>
<td>Undesirable</td>
</tr>
<tr>
<td>The robot moves the user’s arm in an unsafe manner</td>
<td>User’s arm may be injured</td>
<td>Moderate</td>
<td>Probable</td>
<td>During prototype use, attendant will set parameters so as to not allow the robot to move the arm around unless the user initiates movement, forces will be set for safe movement.</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Device may fall if not properly secured</td>
<td>Physical harm</td>
<td>Moderate</td>
<td>Probable</td>
<td>The device will be clamped/weights will be put on the device and tested before use.</td>
<td>Intolerable</td>
</tr>
<tr>
<td>Device may fall if used in the vertical position</td>
<td>Physical harm</td>
<td>Moderate</td>
<td>Probable</td>
<td>The device will be secured, if unable to secure, the power to the device will be cut off and the device will be used to test range of motion only</td>
<td>Intolerable</td>
</tr>
<tr>
<td>Harm</td>
<td>Result</td>
<td>Severity</td>
<td>Probability</td>
<td>Method to Minimize Risk</td>
<td>Risk After Precaution</td>
</tr>
<tr>
<td>------</td>
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<td>-----------------------</td>
</tr>
<tr>
<td>The device could become unstable due to software problems</td>
<td>The mechanical arm may thrust out</td>
<td>Moderate</td>
<td>Occasional</td>
<td>Software controls in place to prevent instability. If the attendant needed to suddenly stop the device arm, the user interface can be closed, the reset button can be clicked on or in the games mode, the EXIT button can be clicked on. Attendant will be present at all times to monitor. Emergency stops in place to cut off power in case the device does become unstable</td>
<td>Tolerable</td>
</tr>
<tr>
<td>The device could experience mechanical fatigue over time</td>
<td>The output force of the motors would be reduced, or the motors would fail</td>
<td>Low</td>
<td>Remote</td>
<td>The device may need to be recalibrated and adjusted</td>
<td>Negligible</td>
</tr>
<tr>
<td>Improper storage</td>
<td>Device could be damaged and not operate</td>
<td>Low</td>
<td>Remote</td>
<td>Label to state use and store in dry, indoor, room condition environment</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Device could be dropped while being transported</td>
<td>Pain from the weight of the device</td>
<td>Moderate</td>
<td>Remote</td>
<td>Educate so that those transporting are aware of the weight of the device and appropriate way to transport.</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Erroneous data transfer</td>
<td>Unexpected behaviour</td>
<td>Moderate</td>
<td>Improbable</td>
<td>The software will shut off power to the system if it detects error. There will be physical and software emergency stops available. Prototype will not be used with intelligence</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Data boards fail</td>
<td>Device will not work</td>
<td>Very Low</td>
<td>Remote</td>
<td>Attendant will check during startup and calibration.</td>
<td>Negligible</td>
</tr>
</tbody>
</table>
Chapter 8. Focus Group

A focus group of therapists was gathered to evaluate the prototype design for an upper limb robotic rehabilitation system. The purpose of the focus group was to use gathered information to refine the features, specifications, and user interfaces of an upper limb robotic rehabilitation device.

8.1 Research questions

1. How do therapists view technology in stroke rehabilitation?
2. What features are necessary in an acceptable upper limb RRD?
3. Is the ROM of the prototype adequate?
4. How large should the device be?
5. How much would therapists pay for such a device?

8.2 Methods

A group of stroke therapists was consulted with regards to their satisfaction with current technology used to treat stroke survivors and the features of the prototype (Chapter 6). Data collected from the survey (Chapter 5) were analyzed to develop strategic questions for the focus group sessions. These questions, as well as the prototype were presented to the participants for critique and input. For more information on the structure of the focus group, see Appendix E. The discussion guide, as well as the information and consent form was approved by the appropriate institutional research ethics boards.

8.2.1 Participants

The participants included therapists (physiotherapists and occupational therapists) from TRI and members from the design team, and the moderator for the sessions was a professional moderator.

Therapist participants included in the study had to have at least two years of experience working with upper limb rehabilitation with stroke survivors and had to be permanent
employees at TRI. Therapists were informed by the Corporate Professional Leader of Occupational Therapy and Clinical Educator for TRI that this study was being conducted. If they were interested, therapists were instructed to contact the research team. Participants were required to review and sign an information and consent form (see Appendix F).

8.2.2 Focus group setup

Therapists were asked to fill out a demographic form (see part I of Appendix A) when they arrived. They were seated around the prototype device with the moderator at the head of the table and the design team members at the edges of the room. One design team member wrote down participant comments on the flip chart, a second member set up and ran the prototype, and a third member videotaped the discussion. The room had a projector connected to a computer, a flip chart to write down ideas, and the prototype on a large table. The moderator was given the discussion guide (Appendix E) days before the focus group to review. This discussion guide was then reviewed by the design team and the moderator before the focus group to clear up any points in the discussion guide.

The moderator started with general questions about the current state of technology and upper limb stroke rehabilitation. The researchers then introduced the prototype and they were asked to interact with the prototype. The prototype was initially set to no resistive/assistive forces. However, later with some therapists it was set to resistive forces and assistive forces. Not all therapists were able to experience the resistance and assistance the device could have provided. In addition resistance and assistance were not set at maximum capacity, but at lower forces to ensure safety of the users. The moderator would at times ask each of the participants to rate the product, or their level of satisfaction with something based on a scale of one to ten, with ten being a high, satisfactory rating, and one being a low, unsatisfactory rating.

Participants were allowed to leave at any point during the focus group and were issued their compensation upon departure. The focus group lasted approximately 80 minutes, with three therapists having to leave around 60 minutes.
8.2.3 Data analysis

Analysis of the focus group discussion was done as per recommendations from Krueger and Casey [111]. Design criteria were derived from the moderator’s and design team’s notes and from a post-analysis of the video recordings of the sessions, which included a transcript of the video recorded sessions along with annotations of observations and activities. Key visual ideas from the flip chart were saved and compared with verbal comments.

Techniques for analyzing the results of the focus group included:

- Identifying comments that were frequently mentioned,
- Manually doing a qualitative analysis to determine themes that arose,
- Responses and impressions to the prototype

When ratings were given by the therapists, these were averaged over the seven therapists who participated.

8.3 Results

8.3.1 Therapist demographics

Seven therapists participated in the focus group. According to the self-reported demographic sheets returned, there were three physiotherapists and four occupational therapists. They all had Master’s degrees in their fields and all were employees of TRI. Four had 1-5 years of experience in stroke therapy, two had 6-10 years of experience, and one had more than 10 years of experience. They had all treated populations of adults (18-64 years old) and senior adults (65 years old and over). One person had experience in treating youth (11-18 years old). They had experience working in a rehab hospital setting, with two in acute care settings. In addition, two had worked in long-term care, three had worked in outpatient clinics, two had worked in home care, and one had worked in a home-based private practice.

The therapists reported using many different approaches to therapy. They used the NDT (7), repetitive task training (7), splinting or orthotics (6), CIMT (5), mental practice with motor imagery (4), electrical stimulation (3), high intensity or practice (2), motor relearning program
propriceptive neuromuscular facilitation (Brunnstrom) (2), EMG feedback (1), and functional strengthening (1). It is important to note that none of them had used robot assisted rehabilitation in the past.

8.3.2 Current technology and stroke therapy

Therapists discussed their satisfaction with current technology for stroke upper limb rehabilitation. When asked about present level of satisfaction with available technology, the participants responded that they had a low level of satisfaction, with an average rating of 3.6 out of a possible 10, with 10 being very satisfied. Participants had tried to use motion sensing games like the Sony EyeToy (www.sony.com). They had also used mechanical orthotic devices such as the SAEBO (Saebo, Charlotte, NC, www.saebo.com). The most relevant available solutions they found were the Biometrics system (Biometrics Ltd., Ladysmith, VA, www.biometricsltd.com), the SAEBO orthotic, and the Dynavision (Dynavision, Markham, ON, Canada, www.dynavisiond2.com). The current tools were tools for patients who had some level of upper limb functioning. One participant expressed that her patients were often not motivated to use these tools. Some devices, like the driving simulator, would cause motion sickness. However, there was a lack of devices for the lower functioning patient.

They found that the set up of current devices had been time intensive and challenging and limited the amount of time they were able to spend with their clients. Some of the software they had used had several menu and page selections, which were impractical for clients with cognitive challenges. One therapist said in terms of technology used in the clinical setting, “The faster you can have it set up and ready to use, the more likely we will use it. We don’t use it as much as we could.” Set up would also need to be easy for home use as well since often their clientele was older and the use of technology was foreign to them. Many times their clients would not see the benefit in using technology.

None of the therapists used anything robotic for the upper limb for brain injury or stroke; however if there was something appropriate, therapists were willing to use technology. Many felt they had not “landed on the right tools yet” and felt there was potential to use more tools.
Therapists expressed a limited access to these devices in clinic and at home due to the hospital often having one or few devices.

Therapists expressed the need for more research in demonstrating a device was able to produce measurable benefit. It was found by the therapists that the impact of current devices they used was limited, especially for the older patient population who had cognitive challenges.

### 8.3.3 Features necessary in an upper limb stroke rehabilitation device

Therapists discussed what they would desire or require in an upper limb stroke RRD. Some desired attributes were cost effectiveness, flexibility and customization, measurable benefits and measurable changes to the patient impairment. Therapists desired a device to be simple, easy and quick to set up, one that would require minimum supervision. They desired a device that would essentially ‘plug and play’, or have one button to start the therapy.

Therapists believed that in order for stroke survivors to have increased access to a RRD, a rental or lease program would need to be created to give patients the option of using the device at home without a major financial investment. Therapists could have a device in the clinic or hospital for training purposes and other devices could be leased by patients.

A device would need to show proven benefits to both therapists and stroke survivors. It was believed that if stroke survivors understood the proven benefits, they would have more motivation to use such a device. A way to show benefit would be to have the device measure change in the stroke survivor’s progress in a quantitative way. Current patient progress was felt to be highly subjective and lacked quantitative measures.

A device would need to be customizable to different patient sizes, needs, and competency levels. Variations in resistance would allow therapists to increase resistance as the patient would show improvement. Customizable programs would need to allow for different levels of comprehension, cognitive abilities, and motor skills of the stroke patient population.
8.3.4 Current prototype critique

When therapists were shown the prototype of the rehabilitation robot they took turns using the device. Most therapists would have liked to see more ROM and felt that the device was unsafe for clients to use alone, predominantly due to trunk instability. All felt that the device was too large. The average ROM satisfaction rating was an average of four out of a possible scale of ten, with ten being completely satisfied. It was seen to be able to mimic only one type of exercise, and that was felt to not be enough. Therapists would have liked to see something with elbow flexion against gravity, elbow extension, or something that would work the grip. They were concerned that the two DoF were too limiting and would have liked to see more DoF. Although it was shown in the vertical position as well, therapists thought it would be best to not move the device once it had been set up. It was felt that the device had “basic movement features, with basic range of motions.” Although the device was restricted in planar movement, therapists preferred having a device with actuated movement than to a device with more degrees of freedom that was not actuated. Many felt that one of the advantages of the prototype was that it could help those with higher levels of impairment, as there was a lack of devices to aid those with higher impairment. It was felt that there were already many other activities those with lower impairment could participate in.

Although they desired a device that could be used at home, it was felt that the set up would be difficult for a typical user if used at home. The ease of use was felt to be 3.6 out of a scale of 10 as patient positioning was the biggest concern. There was concern about the electrical wiring between the electrical and mechanical cases, as they were not sure it would be easily set up. Those in a wheelchair may need more time to adjust their position. They were concerned about the patient trunk area while using the device, as patients may not have correct body positions, which would affect their therapy. It seemed like a caregiver or therapist needed to be present while the patient used the device, however therapists would like a device where there could be minimal supervision. A device which had a predictable movement pattern to reinforce correct movement would be good, especially at home to
reinforce correct motor patterns. Some felt that some of their clients would not be cognitively capable to operate the device.

Therapists were interested in a device that would give feedback, for example, forces and trajectories. They desired a device that would print out reports, which included arm inflections. However numerical measurements were not felt to be good enough feedback, as sometimes these numbers were not intuitive. Some suggested having a randomized three minute video recording with timeline information to understand how the patient was using the device. They would like functional goals that would be defined and measured. An example was given of a functional goal for the lower limbs – devices that measures how much a patient has walked. One therapist felt like her patients would not necessarily volunteer the right information so having information that a device could measure and a therapist could see would be beneficial.

The idea of a virtual therapist/coach avatar was discussed, as patients would require encouragement throughout their therapy. Motivating goal oriented feedback, could include such statements as, “well done, you have reached the target”. One example quoted by a therapist was the Nintendo (www.nintendo.com) “Wii yoga instructor,” who instructed the player to be seated in front of the monitor and provided step by step instructions for the yoga poses. This was seen as a potential solution to solve set up problems as well as positioning problems. Another therapist suggested adding a voice command every 25 seconds to mimic therapist instructions. Another therapist had wanted to add pictures of therapists and to record their voice to motivate patients while the patient was using the device at home. An avatar could also alert patients with a visual and/or audio alarm if they were to deviate from the prescribed program.

Biofeedback was seen as a desired feature by some therapists to allow therapists and their clients to have information relating to joint position, muscle use and activation. The ability for a device to detect which muscles would be active, how they would be positioned, and compensatory movement would be highly desired. Visual, audio, and tactile feedback was seen
as critical features for the device. One therapist said regarding stroke survivors using the device, “The more information we have about them, the better.”

Suggestions for end effectors included having a flat surface for the hand, having a longer supportive end effector. When asked if they would prefer an exoskeleton, one therapist said she would be concerned about the stroke survivor’s arm swelling within the exoskeleton or the problems with skin issues, especially if the clients have a lot of high tone and are putting a great deal of force into it. It was noted that the end effector caster wheel had the possibility of creating marks on the table; a problem that should be addressed.

Motivation with fun games was also seen as an important part to a rehabilitation robotic system. They desired visually motivating games and activities which would help their patients be more compliant with exercise programs. It was suggested that these would involve exercise programs which were more individualized. Similar exercises with different goals could be uniquely customized to each patient. The quantity and intensity of the exercises could be individualized as the device could anticipate different ranges of motion, which in turn could be linked to muscle movements.

In terms of the device’s size it was thought that the device was too large, that portability would be a “must”, especially if it were to be used at home. It was felt that the device should be half the size. It should come with a laptop as many of their clients do not have laptops or computers. And the total weight should be between 5 to 10 lbs. The device would need to have more rounded edges to prevent injury.

Some therapists felt that the main feature of the device was adequate resistance. Therapists rated the resistance to be 7.7 out of 10. When asked whether they would choose a device that had more degrees of freedom over a planar device that could assist, they would choose a device that could assist. One therapist said, “I think having the ability to assist the patient is really key because we don’t have anything to use with a lot of patients, so I wouldn’t want to give that up.” It was felt that aiding their clients to get movement started was very difficult, but once they had movement there were many more options available. Resistance was not seen to be very important as that could be found in other places.
When asked about how much they or their hospital would pay for such a device, many were unsure. One therapist suggested $10,000, another suggested $5,000. When the moderator asked therapists to vote on the price being less than $5000, all the therapists raised their hands. It was felt that if it were priced at $5000, there would be a higher likelihood of purchasing more units. One therapist suggested that she could recommend her patients renting the device for $50 a month.

Overall, therapists seemed enthusiastic about developing a RRD. They wanted to see the final device and expressed that they have been waiting for years for something like this to be designed. Therapists saw the potential in the project and would like to see the clinical trials. They were appreciative of being consulted. One participant said, “This is great. It’s much closer than anything that I have seen there.”

8.4 Discussion

Satisfaction level with current state of technology was very low, indicating there is room for RRD development, especially for the development of technology for stroke survivors who have lower functionality and higher impairment. Technology for those with lower functionality would need to include more assistive features and less resistive. The device would need to be more intelligent, to know when the stroke survivor is in pain or has joint misalignment, and would need to be more intuitive and easy to use. For higher functioning stroke survivors, it seemed that there were tools out there on the mass market which could be used, such as the Nintendo Wii (www.nintendo.com) and the Microsoft Kinect (www.microsoft.com). These were not perfect as it seemed to take too much time to set up and the games were not geared to those with stroke.

Any type of device used at home would need to be extremely easy and intuitive to use. User centered design may be imperative for designing these types of devices, as what may be intuitive for a younger audience with no impairments may not be intuitive for the stroke population. User centered design could be used to design games and activities for a cognitively challenged, older population. User centered design must go beyond caregivers and
therapists and must work with stroke survivors who are older or those who have cognitive challenges to iteratively test programs and activities which would be useful.

Motivating patients to comply with carrying out exercises at home was another key factor therapists mentioned. This goes beyond having a program or device that is intuitive and easy to use to something stroke survivors will want to use. If devices and programs are developed which are useful to therapists, but do not interest stroke survivors, there may be low compliance in the actual use of the device. What is seen as motivating, for example seeing quantitative improvement or having engaging activities may be different for the therapist compared to the stroke survivor. Focus groups with stroke survivors would be a necessary component in developing a device which is not only usable, but which is motivating.

As none of the therapists had experience with rehabilitation robotics, it may have been hard for them to discuss the device without having a reference to compare to. In addition, they had limited time to try the prototype during the focus group time. Not having this reference and not using the robot, they may not have known the advantage of having a robotic device. As the survey (Chapter 5) has shown however, this may be the case for 94% of therapists. Therapists who have not used robotic rehabilitation may have a certain standard in mind before being open to try robotic therapy with their patients. For example, they may envision a small portable actuated device, when in actuality the devices on the market are much larger than they envision. Or they may envision a device that is capable of many DoF to facilitate movement, when a 2 DoF device may be usable as well.

Literature has shown that robotic therapy is effective, however therapists who have no experience with robotic therapy may be unsure. As one therapist suggested, therapist buy-in could be addressed through research clinics with robotic devices. Clinics could be set up with robotic devices which would allow therapists to experience using the device. Therapists could experience tangible benefits first hand and may perceive the value of the device to be higher than without the experience. These clinics would be limited of course, but once initial buy-in is obtained, other therapists would see the value (if it is found) and costs could be lowered enough to overcome the initial financial hurdle.
Customization of rehabilitation programs may include different end effectors and different programs, but at another level it would mean some type of artificial intelligence that could learn how the user is progressing and make decisions in assistance or resistance based on user progression. The sensory inputs for this level of customization would need to include haptics to allow the device to learn how the user is dealing with different activities. Haptic devices not only allow the user to sense virtual objects, they sense how the user is doing. Information gathered can be translated into valuable information to make decisions when a therapist is not present, such as whether or not the user is in pain. Other sensors such as EMG, computer vision, and speech recognition could also be used to enhance the decision making process for the system. The more the rehabilitation system is able to sense, the more intelligent its decisions could be, the more the device would be usable in the home environment.

8.4.1 Prototype changes

There are several changes that need to be incorporated into the next iteration. The device would need to have more ROM than it currently has. This can be easily done by increasing the link lengths. Therapists also desired more DoF, however this is less easily incorporated into the existing system.

There were set up challenges by making the device housed in two cases. In order to facilitate ease of set up, the device would need to be housed in one case. This could be done if the link arms were an interior barrier separating the mechanical and electrical components and if the link arms were made of non-conducting material.

The device would need to be smaller as well. Although therapists rated the amount of force to be 8/10, they did not experience the maximum assistive or resistive forces of the device. The power of the forces of the device could be decreased by decreasing the capstan way size, while at the same time increasing the link arm size. It would seem that if the device were geared toward lower functioning stroke survivors, power could be reduced significantly, thus reducing the weight and size.
Therapists in this group were very concerned about proper positioning of the stroke survivor. This may be due to training from influences from the NDT approach which emphasizes proper positioning and normal muscle movement. The next prototype that would be presented to therapists must include a system which senses posture and arm deviations. This could be done with a computer vision system which could sense the person’s shoulder, trunk, and elbow. A visual avatar of the stroke survivor could be used to give the stroke survivor feedback on their body position. Audio and visual cues could be programmed to instruct end users in repositioning their bodies if they are not in the correct position. Biofeedback such as EMG biofeedback could also be used, although this would be more difficult to set up for the stroke survivor at home. Yet it may be used in a clinic setting where the therapist is able to set up the EMG leads.

It has been shown that virtual reality environments can aid in motor rehabilitation and the gains made in the virtual environment are transferable to the real world [31]. Along with the patient avatar there could be a therapist avatar or coach who could give audio and visual feedback to the patient, such as encouragement, and instructions on how to use the device. The therapist avatar could also virtually demonstrate correct movement and give visual feedback to the patient. The avatars could be presented side by side to aid in understanding correct movement. It has been shown that learning through imitation can happen [112]. For those who have very low functional movement, this aspect of imitation learning may be beneficial through allowing the stroke survivor to see correct movement and at the same time have the robotic device move the arm in the correct movement pattern.

Additional focus groups, especially those involving stroke survivors and their caregivers, would be necessary in further developing and evaluating this device. Additional focus groups with therapists, stroke survivors, and caregivers would also be necessary to evaluate further devices. Finally, usability testing of the device would be necessary before clinical trials could be conducted.
8.5 Focus group limitations

The amount of time the participants had to discuss was limited to the participants’ lunch break. This limited the amount of interaction participants could have had with the RRD, as well as their time to discuss. Ideally there would have been more focus group sessions and more time to discuss the topics introduced.

The focus group was conducted in one city and with employees from one rehabilitation hospital. There was only one focus group conducted. Ideally there would have been more focus groups from different settings and different countries. As the survey information showed (Chapter 5), different countries had statistically significant differences in therapy approaches and use of RRDs. This would influence the discussion of the design of such a device.

None of the therapists had experience with robotic rehabilitation and so they did not have anything to compare the prototype to. Thus they did not have a frame of reference. If there had been more time, the prototype could have been compared with other RRDs on the market. This may have generated different discussion.

Although therapists are knowledgeable about the needs of their clients and they are one group of end users for the device, the focus group did not include stroke survivors or their caregivers. Due to time constraints, focus groups for the latter groups were not conducted.
Chapter 9. Biomechanical Analysis

This chapter details a kinematic and kinetic analysis of the upper arm using the RRD developed.

9.1 Motivation and research questions

Understanding the kinematics and kinetics produced on the upper limb joints while a user is interacting with the RRD can aid in determining the necessary workspace and force requirements. Measured values were compared to reference values in the literature of joint angles and moments while performing ADLs.

9.1.1 Research questions this biomechanical analysis hopes to address are:

1. What are the joints (shoulder, elbow, wrist) ranges of motion while the user interacts with the RRD?
2. What are the maximum moments produced on the joints while the user interacts with the RRD?
3. How do the values in 1 & 2 compare to measured values in the literature for ADLs?
4. Is the workspace of the device sufficient to rehabilitate the joints to the ROM for typical ADLs?
5. Is the force produced by the device sufficient to rehabilitate the joints to the moments for typical ADLs?

9.2 Methodology

9.2.1 Experimental set up

Four healthy subjects with no current upper limb problems participated in this trial, see Table 9-1. Height and weight were self reported. The upper arm was measured from the right acromion to the lateral condyle of the right elbow. The forearm was measured from the lateral condyle to the radial styloid. Shoulder circumference was measured from the axilla to the
acromion. Elbow width was measured between the medial and lateral condyles, wrist width was measured between the radial and ulnar styloids.

Table 9-1. Biomechanics trial subject anthropometric data
All length measurements in cm unless otherwise stated

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Height</th>
<th>Weight (kg)</th>
<th>Upper arm length</th>
<th>Forearm length</th>
<th>Shoulder circumference</th>
<th>Elbow width</th>
<th>Wrist width</th>
</tr>
</thead>
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</tr>
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<td>F</td>
<td>151</td>
<td>50</td>
<td>29</td>
<td>23</td>
<td>37</td>
<td>6.5</td>
<td>5.0</td>
</tr>
<tr>
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<td>F</td>
<td>157</td>
<td>159</td>
<td>32</td>
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<td>62</td>
<td>11.9</td>
<td>7.0</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>170</td>
<td>73</td>
<td>34</td>
<td>26</td>
<td>50</td>
<td>8.2</td>
<td>5.5</td>
</tr>
</tbody>
</table>

A seven camera Vicon system (Vicon Motion Systems, Ltd., Oxford, England, www.vicon.com) was used to capture the motion of the arm while using the RRD. Twelve reflective markers were placed on the bony landmarks of the following locations of each subject: Shoulder acromion (right and left), the jugular notch, C7, lateral condyle of the right elbow, radial styloid of the right wrist, ulnar styloid of the right wrist, second knuckle of the right hand, right mid forearm, right mid upper arm, iliac crest (right and left). The Vicon system was set to capture at 100 Hz.

The RRD was placed on a 40 cm x 60 cm AMTI (Watertown, MA, www.amti.biz) six axis force plate to measure the moments on the joints. The force plate was set to record data at 1000 Hz. Eight markers were placed on the robotic device for the static picture for the Vicon system. During the trial, one marker was taken off the end effector due to hand placement. Thirty pounds of weights were placed on the device to assure the stability of the device. Markers were placed on the four corners of the seat as well. A static recording of the system was taken after each trial.

EMG bar sensors (Delsys, Boston, MA, www.delsys.com) were placed on major muscle groups to detect muscle movement. EMG sensors were set to capture data at 4000 Hz. Alcohol was used to cleanse the skin and an abrasive tape was used to prepare the skin further. Six electrodes were placed on the belly of the following muscles: biceps, triceps, anterior deltoids, posterior deltoids, flexors, and extensors. With the subject completely relaxed, a baseline EMG was taken. Three isometric maximum voluntary contractions (MVC) per muscle were recorded.
by having the subject resist against an opposing force for three seconds, then a rest for five seconds, three times [113]. These data will not be reported here as it is out of the scope of the current thesis.

Figure 9-1. Biomechanic measurement set up
Reflective balls are the Vicon markers, taped wire electrodes are the EMG leads

Subjects were asked to sit up straight in front of the robotic device with arm fully extended at 90° in the plane of elevation while the device’s arm was fully collapsed, see Figure 9-1. Subjects were asked to place their hand on the end effector of the robot and move it back and forth in a sagittal reaching motion five times (see Figure 9-2), then a transverse reaching motion five times, for each setting (see Figure 9-3). Subjects were asked to reach within their comfortable ROM or as far as the device would allow them to.

Figure 9-2. Sagittal reaching motion schematic

The robot was set in damping increments of 10 Ns/m from 0 Ns/m to 50 Ns/m. Spatial measurements were taken with the Vicon system, force measurements were taken with the AMTI force plate as well as recorded with the robotic device, and EMG signals were taken with the EMG system. All signals were synched through the collection of the force plate data, which
was done through a LabView (National Instruments, Austin, TX) interface. A signal was sent to start the kinematic (Vicon) data collection to LabView and another signal was sent from the Delsys EMG to Simulink.

![Note: Drawings not to scale](image)

**Figure 9-3. Transverse reaching motion schematic**

### 9.2.2 Data analysis

#### 9.2.2.1 Kinematic data

Kinematic data were extracted from the Vicon software and analysis was done on Matlab R2009a, see Appendix G for the Matlab code. Since the ROM was more important to the development of a RRD, maximums, minimums, and total ranges of joint movement were extracted. The raw spatial data were filtered with a fourth order Butterworth filter [114]. A fast fourier transform (FFT) analysis was conducted to determine the cutoff frequency. It was assumed that the robot on the force plate on the desk was stationary.
Angles were calculated between segments joining the Vicon markers, see Figure 9-4. Wrist angles were calculated as the angle between the segment marked by the 2nd knuckle and medial wrist and the segment marked by the medial wrist and the elbow with a neutral angle (0°) being a straight line between the finger marker, wrist, and elbow markers. It was assumed that there was negligible flexion and extension of the wrist as well as negligible pronation and supination of the forearm. The majority of the angle changes within the wrist were assumed to be due to radial and ulnar deviations. Elbow angle was calculated as the angle between the segment marked by the medial wrist and elbow and the segment marked by the elbow and right shoulder. The neutral (0°) being a straight line between the wrist, elbow and shoulder markers (elbow in extension). The shoulder angles were calculated as the angles between the trunk coronal axes and the upper arm using the globe system. The shoulder plane of elevation (roughly corresponding to shoulder abduction/adduction) [115] angle was calculated using the segment between the right and left shoulder markers and the segment between the elbow marker and the right shoulder marker. The neutral (0°) being a straight line between the shoulder markers and the elbow marker (shoulder in abduction). The angle of elevation (corresponding to shoulder flexion and extension) [115] of the shoulder was calculated using the segment marked out by the elbow and right shoulder markers and the segment marked out by C7 and the midpoint between the iliac crest markers. The neutral (0°) being the arm in the anatomical position (in extension, next to the body). Rotation angle of the shoulder was assumed to be negligible.
After the data were filtered, maximum and minimum angles were then calculated for each trial. These angles were averaged within the same type of movement over the six trials (settings from 0 Ns/m to 50 Ns/m) to determine the ROM experienced by each joint for each subject. To determine whether or not the ROM for the device would be adequate, the ROM for each joint was compared to a reference value. The total ROM, calculated as the differences between the maximum and minimum angles, were compared to published ROMs. While there are no published data on the exact ROM that were studied here, there were data on maximum ranges of motion for activities of daily living. Murray 2004 measured the angles, forces, and moments of joints of the upper limb when performing ten common ADLs [116]. The maximum ranges of motion (the minimum subtracted from the maximum) for the elbow and shoulder were used to compare the shoulder and the elbow data. Ryu 1991 studied wrist movement in 31 ADLs and reported the extreme range of wrist motion [117]. These ranges were used to compare the wrist data in this study.

9.2.2.2 Kinetic data

Kinetic data were calculated by combining the force plate data collected through the LabView software and the kinematic data collected through the Vicon software. The force plate baseline was measured as the first ten seconds of the first trial of the first subject when there was no movement. This baseline was subtracted from all the remaining data. The data were then down sampled by a factor of 10 to match up with the kinematic data. The data were synched with the Vicon data, with data points before the synch deleted. Data were then filtered back and forth (to remove any phase changes) with a second order Butterworth filter with a cutoff frequency which was determined using an FFT spectral analysis of the data. Maximum forces were extracted for each trial and each subject. These were compared to the device’s damping coefficient setting.

A two-dimensional transverse plane link segment model was used, see Figure 9-5. The joints were considered to be hinge joints for this model. Anthropometric data from Winter 2009 were used to determine center of mass (COM), radius of gyration, and segment weight [114]. The upper arm segment was calculated as the distance between the shoulder and
elbow. The forearm segment was calculated as the distance between the elbow and wrist, and the hand segment was calculated as the distance between the wrist and 2\textsuperscript{nd} knuckle of the hand. Linear and angular data were calculated from the Vicon data.

![Diagram of joint segments](image)

**Figure 9-5. Link segment model of the upper limb.**

Forces at the joint segments were calculated in the XY (transverse) plane, as this was the plane of interest with regards to the robotic device. As data were used to extract maximum forces and moments generated, calculations were simplified by assuming the center of pressure to be directly under the finger. Moment of inertia calculated around the COM by equation (9-1), where \( m \) is the mass of the segment and \( \rho \) is the radius of gyration. Using the parallel axis theorem, the moment of inertia around the end of the joint is given by equation (9-2). Using Newton’s second law of motion (equation (9-3)), forces at each joint were separately calculated for each direction (\( x \) and \( y \)) and combined at the end. Moments were calculated using (9-4). Positive moments were counter-clockwise. Positive forces were posterior and to the right of the person. Maximums and minimums were then extracted from each data set and compared to Murray’s data on forces and moments of the shoulder and elbow [116]. Unfortunately, comparable data for the wrist was not found in the literature.

\[
I_0 = m\rho_0^2 \quad \text{(9-1)}
\]

\[
I = I_0 + mx^2 \quad \text{(9-2)}
\]
\[ \Sigma F = ma \]  \hspace{1cm} (9-3)
\[ \Sigma M = I_0 \alpha \]  \hspace{1cm} (9-4)

9.3 Results

9.3.1 Kinematics

Through spectral analysis, a cutoff frequency of 5 Hz for the shoulder was determined. After analyzing the data, it was found that at many points the lateral wrist marker was not detected. It was therefore the medial wrist marker was used to determine the wrist position.

Figure 9-6 shows a representative example of one subject’s sagittal reaching motion hand trajectory traced through the marker on the 2nd knuckle under a damping constant of 30 Ns/m. Figure 9-7 shows a representative example of a transverse reaching motion hand trajectory for the end effector at a damping constant of 30 Ns/m. Starting position is at (0,0) for both types of motion. The subject would be seated to the right of the graph, facing the graph.

Figure 9-6. Sagittal reaching motion hand trajectory (subject 1, damping force of 30 Ns/m).
Figure 9-7. Transverse reaching motion (subject 1, damping force of 30 Ns/m).

Figure 9-8 shows the upper limb joint angles of one subject while doing a sagittal reaching motion under a setting of 30 Ns/m on the device. As this analysis is predominantly concerned with maximum angles, not all subjects’ kinematic data were shown. Figure 9-9 shows the upper limb joint angles of one subject while doing the transverse reaching motion under a setting of 30 Ns/m for the device.
Figure 9-8. Joint angles for sagittal reaching of subject 1 (RRD setting: 30 Ns/m)
Angles in degrees, shoulder plane of elevation roughly corresponds to shoulder adduction/abduction. Shoulder angle of elevation corresponds to shoulder flexion/extension.
Figure 9-9. Joint angles for transverse reaching motion of subject 1 (RRD setting: 30 Ns/m)
Angles in degrees, shoulder plane of elevation roughly corresponds to shoulder adduction/abduction. Shoulder angle of elevation corresponds to shoulder flexion/extension.

Table 9-2 gives the range of joint motion data during sagittal reaching. The averages of the minimum and maximum joint angles over the six trials are given, as well as the standard deviations for each. When compared to the reference values, the wrist ROM ranged from 26% to 47% compared to a functional ROM for the wrist from Ryu’s data [117]. The ROM for the
elbow ranged from 27% to 54% compared to Murray’s data [116]. The ROM for the shoulder ranged from 110% to 135% for shoulder plane of elevation and 48% to 71% for shoulder angle of elevation. There was some difficulty detecting the markers on the iliac crest of subject 4, therefore the data were not included.

Table 9-2. Sagittal reaching minimum (Min) and maximum (Max);
Averages of six trials for each subject (n=6) with standard deviations. Reference values found in Murray [116] and Ryu [117], n/a - insufficient data, †Murray used adduction/abduction

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder plane of elevation</th>
<th>Shoulder Angle of elevation</th>
</tr>
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<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
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<td>5.2±2.5</td>
<td>20.9±0.9</td>
<td>46.4±2.1</td>
<td>120.3±1.4</td>
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<td>2</td>
<td>8.5±4.5</td>
<td>29.0±15.2</td>
<td>42.3±4.3</td>
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<td>28.4±4.3</td>
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<td>120.5±1.5</td>
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<tr>
<td>4*</td>
<td>11.9±3.5</td>
<td>39.6±1.1</td>
<td>40.5±3.0</td>
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</tr>
<tr>
<td>Murray†</td>
<td></td>
<td></td>
<td>15.6±6.6</td>
<td>164.8±8.0</td>
</tr>
<tr>
<td>Ryu</td>
<td>-21</td>
<td>38</td>
<td>14.7±7.6</td>
<td>111.9±7.4</td>
</tr>
</tbody>
</table>

Table 9-3 shows the range of joint motion data during transverse reaching. The system had trouble detecting the right and left iliac crest markers on subject 4, so the data for the shoulder angle of elevation were not included. The system also had difficulty detecting the wrist marker on subject 2, therefore the data on wrist and elbow joints were not included for that subject. The averages and standard deviations are shown for each minimum and maximum angle. The wrist ROM was 103% to 186% when compared to measured functional ROM for the wrist from Ryu’s data [117]. The ranges of motion for the elbow were 29% to 58% when compared to the reference data. The shoulder adduction/abduction (plane of elevation) ranges of motion were 144% to 201%. These values may be exaggerated as Murray used adduction/abduction and the plane of elevation was used in this study. The shoulder flexion ROM (angle of elevation) were 54% to 81% compared to Murray’s reference data [116].
Table 9-3. Transverse reaching minimum (Min) and maximum (Max)
Averages of six trials for each subject (n=6) with standard deviations. Reference values found in Murray [116] and Ryu [117], n/a - insufficient data, †Murray used adduction/abduction

<table>
<thead>
<tr>
<th>Subject</th>
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<th>Wrist Max</th>
<th>Elbow Min</th>
<th>Elbow Max</th>
<th>Shoulder plane of elevation Min</th>
<th>Shoulder plane of elevation Max</th>
<th>Shoulder Angle of elevation Min</th>
<th>Shoulder Angle of elevation Max</th>
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<td>121.7±2.1</td>
<td>0.02±0.0</td>
<td>100.3±1.50</td>
<td>7.28±1.6</td>
<td>68.4±1.2</td>
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<tr>
<td>2*</td>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
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<td>n/a</td>
<td>n/a</td>
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<td>39.5±3.1</td>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Murray†</td>
<td></td>
<td></td>
<td>15.6±6.6</td>
<td>164.8±8.0</td>
<td>-20.1±9.2</td>
<td>39.7±6.9</td>
<td>14.7±7.6</td>
<td>111.9±7.4</td>
</tr>
</tbody>
</table>

9.3.2 Kinetics

The data were filtered with a cutoff frequency of 5 Hz. Maximum force measurements in the transverse plane (combined forces from the anterior/posterior axis and in the medial/lateral axis) taken from the force plate for each subject during each trial.

The maximum forces and moments of each joint were calculated for each subject at each setting Figure 9-10 and Figure 9-11 show the maximum sagittal and transverse reaching forces and moments for each joint in the arm for subject 1, other subject maximums are in Appendix H. The data for sagittal reaching at 10 Ns/m had some data points missing and therefore the values may inconsistent with the other data points.

The maximum amount of forces and moments for the sagittal motion used by each subject over all the trials are summarized in Table 9-6 and 9-7. Positive force for the anterior/posterior axis moves to the posterior, negative force is moves to the anterior. Positive force for the medial/lateral axis is positive moves to the subject’s right; negative force for moves to the subject’s left. The percentage of the positive and negative force were calculated by dividing Murray’s reference values [116] for the elbow and shoulder. There were many data points missing for subjects 2, 3, and 4, thus the data reflected for these subjects were incomplete.
Tables 9-9, 9-10, and 9-11 summarize the maximum amounts of force and moments for the transverse motion used by each subject over all the trials. Positive force for the anterior/posterior axis moves to the posterior, negative force is moves to the anterior. Positive force for the medial/lateral axis is positive moves to the subject’s right; negative force for moves to the subject’s left. The percentage of the positive and negative force were calculated by dividing Murray’s reference values [116] for the elbow and shoulder. There were no reference values found for forces on the wrist. There were many data points missing for subjects 2, 3, and 4, thus the data reflected for these subjects were incomplete.
Figure 9-11. Transverse reaching max forces and moments on the arm joints, subject 1

Table 9-4. Sagittal motion maximum forces in the anterior/posterior axis; (forces in N)
Maximums of six trials for each subject (n=6), reference is Murray [116]. Positive forces in the direction of the posterior, negative forces in the direction of the anterior

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
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</thead>
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<td>Negative</td>
<td>Positive</td>
<td>Negative</td>
<td>Positive</td>
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</tr>
<tr>
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<td>-20.11</td>
<td>13.95</td>
</tr>
<tr>
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<td>-3.22</td>
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<td>Murray</td>
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<td>-7.2</td>
<td>7.9</td>
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Table 9-5. Sagittal motion maximum in the medial/lateral axis; (forces in N)
Maximums of six trials for each subject (n=6), reference is Murray [116]. Positive forces to the right of the subject, negative forces to the left of the subject

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
</tr>
</thead>
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<td>-11.14</td>
<td>8.29</td>
<td>-3.38</td>
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<tr>
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<td>20.1</td>
<td>-7.4</td>
</tr>
</tbody>
</table>

Table 9-6. Sagittal motion maximum moments of the superior/inferior axis; (moments in N·m)
Maximums of six trials for each subject (n=6), reference values found in Murray [116]. Positive direction is counter-clockwise, negative is clockwise

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Negative</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
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<td>0.69</td>
<td>-4.32</td>
</tr>
<tr>
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<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>3</td>
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<td>4</td>
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<td>-1.46</td>
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<tr>
<td>Murray</td>
<td>-2.8</td>
<td>5.8</td>
<td>-3.7</td>
</tr>
</tbody>
</table>

Table 9-7. Transverse motion maximum forces in the anterior/posterior axis; (forces in N)
Maximums of six trials for each subject (n=6), reference is Murray [116]. Positive forces in the direction of the posterior, negative forces in the direction of the anterior

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Positive</td>
<td>Negative</td>
</tr>
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<td>1.80</td>
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</tr>
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<td>0.41</td>
<td>-4.17</td>
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<td>4</td>
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</tr>
<tr>
<td>Murray</td>
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<td>3.3</td>
<td>-7.2</td>
</tr>
</tbody>
</table>
Table 9-8. Transverse motion maximum forces in the medial/lateral axis; (forces in N)
Maximums of six trials for each subject (n=6), reference is Murray [116]. Positive forces to the right of the subject, negative forces to the left of the subject

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
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<tr>
<td>Murray</td>
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<td>20.1</td>
<td>-7.4</td>
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</table>

Table 9-9. Transverse motion maximum moments of the superior/inferior axis; (moments in N·m)
Maximums of six trials for each subject (n=6), reference values found in Murray [116]. Positive direction is counter-clockwise, negative is clockwise

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
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<tbody>
<tr>
<td></td>
<td>Negative</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>1</td>
<td>-1.08</td>
<td>0.81</td>
<td>-5.52</td>
</tr>
<tr>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>3</td>
<td>-1.14</td>
<td>0.34</td>
<td>-2.67</td>
</tr>
<tr>
<td>4</td>
<td>-1.48</td>
<td>0.55</td>
<td>-2.19</td>
</tr>
<tr>
<td>Murray</td>
<td></td>
<td></td>
<td>-2.8</td>
</tr>
</tbody>
</table>

9.4 Discussion

9.4.1 Range of motion

The ROM differed from person to person depending on the size of their limbs, their seated position, and the type of motion. Data for the ROM for each subject and each joint measured are listed in Tables 9-2, 9-3, 9-4, and 9-5. Unfortunately, many data points were lost while using the Vicon system, so these numbers many not represent the true ROM for each subject. They would however, represent a portion of the ROM, while the actual ROM may be higher than reported. However, from the low standard deviations in Table 9-2, 9-3, 9-4, and 9-5, it could be deduced that there were small deviations between the minimums and maximums of joint angles between trials for each subject. This would indicate the ROM for different damping
coefficient settings of the device were consistent. Larger differences may have been due to markers being undetected and not due to actual differences between trials.

9.4.2 Moments

The maximum moments measured from the data for four subjects are in Tables 9-6, 9-7, 9-8, and 9-9. It would be expected that the moments would increase linearly with the increase of the damping force, however this was only partially the case. The problem lies with the missing Vicon data points as these were used to calculate the moments at each of the joints. The moments recorded do represent a part of the data and may be underrepresented; that is, the actual moments may be higher than reported.

9.4.3 Comparison of ROM and force to ADL values in the literature

It was a challenge to compare kinematic and kinetic data for the upper limb as there were no standard activities for measuring the upper limb movement as there were for the lower limb. Comparisons should be made to ADLs, as these are often the goals of upper limb rehabilitation rather than maximum moments and maximum ROM. Additionally comparisons of ROM and moments were further complicated as the data in the literature were incomplete. However, there were two sources of data which recorded the kinematics and one source which had kinetic data for common ADLs. There were other sources of data as well, however two sources were chosen for ease of comparison. Ideally, common ADL movements would be measured with the subjects involved to understand what percentage of the ROM and moments on the joints the rehabilitation device could account for. The comparisons in the results section can only be used as a general reference as the sagittal and transverse movements were not exactly the same as the movements used in comparison. The comparisons were made as a percentage of the total ROM as different seating positions would affect the minimum and maximum angles. The actual percentage of the ROM and moments are given in Tables 9-2 to 9-9.

The shoulder elevation plane (adduction/abduction) and the elbow angle would be important factors to consider when determining if the device’s workspace was adequate.
While using the device, the shoulder adduction/abduction and elbow angle would govern much of the shoulder and elbow movement along the transverse plane. For the sagittal reaching task, the device seems to provide more than adequate ROM for the shoulder’s plane of elevation - its transverse movement. However, the angle of elevation (sagittal plane) did not seem adequate. In comparing the transverse reaching motion, it was found that there was more than adequate movement for the shoulder in the plane of elevation and the wrist, whereas the elbow and shoulder angle of elevation did not seem adequate. This would be due in part to the device being a two dimensional device. A three dimensional device would be able to provide more ROM for the shoulder angle of elevation. The sagittal reaching motion, in itself may not provide enough ROM for the wrist and elbow. As the device was not tested in the vertical position, the shoulder angle of elevation and the elbow ROM would increase when tested in this configuration.

The device could be increased to allow the elbow more extension. The length of the links in the device could increase by a total of 22 cm to fully accommodate the longest subject’s arm, see Appendix I for link extension calculations. However, this may not need to be increased as the shoulder plane of elevation had more than enough movement and giving the subject a variation of the exercise (i.e. hold upper arm still while moving the forearm and wrist), may allow for more ROM in the elbow.

In looking at the force data, the magnitude of the force should be taken into consideration and not necessarily the signs, as there were different axes used for the reference and the measured forces. The references used localized axes, whereas this set of data used a globalized axis system. Data for subjects 1 and 3 were more reliable as there were many data points missing from subjects 2 and 4. Comparing the force data to the reference, the forces produced on the joints were more than what Murray [116] measured in his common ADLs. This would indicate that the forces may be decreased without compromising the ability of the device to rehabilitate ADLs. Increasing the link lengths by a total of 22 cm would effectively decrease the force on the joints by almost one half (the current link lengths are about 25 cm). Given the maximum forces are at times over 100% for subjects 1 and 3, this could be an option.
9.4.4 Limitations

There were several assumptions made which may have affected the analysis. It was assumed that the movement was entirely in one plane - the transverse plane. Thus, forces along the superior inferior axis were disregarded, as were moments detected along the anterior/posterior axis and medial/lateral axis. It was also assumed that the robot on the force plate was stationary and did not move. The table may have been slight movement which could have affected the data. The center of pressure was assumed to be directly under the second knuckle of the right hand.

Vicon markers which were placed on subjects' would disappear from the camera due to many reasons. Loose clothing would sometimes cover up the markers. Markers may have been blocked by the device or the weights on top of the device. Ideally there would have been more cameras placed to record the data and insure markers were always in the line of sight of at least two cameras. The lateral wrist marker was especially fond of hiding and was taken out of the results, which may have affected the data.

The device was only tested under one position for two types of movements. It would have been useful to test the device in different positions and different movements as this would affect the kinematics as well as the kinetics. The reference values were a composite of many ADLs, not just one type of movement. Testing the device under a variety of positions and movements would aid in fully understanding the kinematics and kinetics of the arm while using the device.

The number of subjects was also a limiting factor. Although the subjects were of different sizes, a larger range of subjects and trials would need to be done to validate the data. Subjects were all healthy, and so may not be representative of the target populations it has been shown that stroke survivors have shown to use different ranges of motion in their activities of daily living[118]. Further studies on healthy subjects as well as stroke survivors are needed.

The ADLs used for comparison may not be appropriate in that those with higher impairments may not be able to move in the full ROM of healthy subjects. The ROM of the device may be adequate enough for lower functioning arms. As the therapist focus group
indicated that they would prefer an actuated device which could aid lower functioning arms, the device’s ROM may be adequate.

9.5 Future work

Understanding the kinematics and kinetics behind arm interactions with the rehabilitation robot would eventually allow for quantification of the rehabilitation process. This would be important for assessing clinical treatments using the device as well as being able to compare different devices [10], [119]. Quantification of arm movements with the device would give a concrete idea of how much the arm is moved and what forces the arm uses. A biomechanical analysis of kinematics and kinetics of similar reaching motions while therapists conduct their therapy would give a better comparison to the data found in this study.
Chapter 10. Conclusion and Future work

10.1 Research Questions

This thesis presented a proof-of-concept study to answer the following research questions, stated in Section 1.4:

1. What role can rehabilitation robotics play in upper limb stroke therapy?

An upper limb robotic rehabilitation device would be a useful tool for therapists. Not only has it proven to be beneficial in past clinical studies, most therapists surveyed (Chapter 5) would be open to purchasing a RRD. A focus group of therapists discussing such a device (Chapter 8), vocalized a lack of technology they could use and a desire for a usable RRD. Therapists surveyed and therapists questioned in focus groups desired a desired a low cost and a portable device which could be used both in a home and in a clinic setting. The focus group desired a device that could be used with minimal supervision to perform repetitive therapy.

2. What form of robotic technology would aid clinicians in upper limb stroke therapy?

Observational studies in Chapter 4 show that therapists could use a small, portable device which would allow therapists to cue or touch their patients. This device could incorporate everyday objects in its use as well as cognitive activities and aid in mental imagery. It would be easy to set up, easy to don and doff, and have minimal set up time. It would allow for different planes of motion and have pain and position sensors.

The survey in Chapter 5 give greater detail as to what properties a RRD would need. The device would need to fit into current approaches to therapy, predominantly repetitive task movements, NDT, and motor relearning. It would need to facilitate many arm movements, especially those common to ADLs. It would allow for trunk stability, be usable in a seated position, give biofeedback to users, and adjust its resistance based on client performance. It could be used in the clinic or at home and would be low cost.

Focus groups detailed in Chapter 8, give further recommendations on for a RRD. Participants desired a customizable device that is able to measure changes in patient
impairment. They would like a device that is simple and quick to set up. Their ideal device would be an end effector assistive device which would have many degrees of freedom, be low cost and lightweight.

3. **What would be the design specifications of a low-cost, usable RRD?**

Specifications for one prototype may be found in Chapter 6, however this prototype did not have the required ROM or DoF a focus group of therapists would like, nor the ability to secure the trunk. The ideal device would be an actuated device housed in one case, have at least 3 DoF, and be less than 5 kg and under $5000. This ideal may be very difficult to achieve with present technology.

10.2 **Summary of contributions**

This research has contributed to the existing body of knowledge in the following ways:

1. Discovered therapist requirements for a RRD through ethnographic observations and a therapist survey.
2. Designed mechanical components of haptic robotic rehabilitation prototype for the arm using survey results and the House of Quality.
3. Evaluated the device with a focus group of therapists and an initial biomechanical analysis.
4. Produced two related publications (Appendix J).

10.3 **Study analysis**

This study attempted to use principles of user-centered design[17] to guide the development of an upper limb RRD. In some ways, the development process was successful, in other ways, challenging.

**Work practices of the user control the development.** This study used observations from therapist workflow, survey results from stroke therapists, and a focus group of stroke therapists to guide the development of an upper limb RRD.
Representatives from end user groups should be actively involved early and continuously throughout development. Representatives of the therapist group were actively involved early and continuously throughout the development. However, due to time constraints and difficulties with recruitment, stroke survivors were unfortunately not involved in this iteration.

The development should undergo many iterative cycles to come up with requirements from the end users. Due to delays in ethics approval and manufacturing, only one iteration took place. Future iterations should involve stroke therapists and stroke survivors, as well as stroke survivor caregivers. Originally there was to be more than one focus group, so the design process could go through many cycles of design, feedback, evaluation, and redesign.

Prototypes should be created early and continuously to visualize and evaluate ideas. One prototype was created to visualize and evaluate. It was hoped that this would be created earlier to allow for more iterations. Future iterations should continue to include prototypes for visualization and evaluation.

The development process should be performed by interdisciplinary teams. The development process involved OTs, PTs, and engineers to develop the prototype. As design flaws came up, the industrial partner decided to make changes in the design. This did not fit in with some of the specifications and as the prototype was in process, it was harder to bring these changes to the focus groups to check if they were good changes.

10.3.1 Lessons to be learned

Valuable time was wasted in waiting for the prototype to be built; this could have been sped up by creating low fidelity prototypes, such as mock-ups, storyboards, and paper prototypes. Therapists and stroke survivors needed to work more closely with the design team in order to come up with a usable RRD. Part of the problem was the location of the engineers working on the robot design and the end-users. The physical distance created a problem for good communication to happen. It was hard to all sit at one table to discuss the design.
10.4 Recommendations for future work

It is recommended that further cycles of iterative design and assessment be incorporated into the development of a RRD. It is recommended that the following changes be made to the RRD for the next cycle:

1. Develop a method to secure the device to a table, so that it does not fall
2. Shrink the device so that it is more portable
3. Lengthen the links to increase the workspace (11 cm per link)
4. Encase all components of the device under one housing
5. Use lighter materials for the arm links and the housing
6. Construct different end effectors including a flat surface, a forearm rest, an handle with buttons
7. Use a non marking ball castor
8. Develop trunk and arm position sensors to ensure proper positioning
9. Develop an intuitive user interface
10. Develop end effectors with therapists which could secure the hand more effectively

It is recommended that more focus groups be conducted to evaluate further devices, especially focus groups involving stroke survivors and their caregivers, as well as additional focus groups with stroke therapists. Conduct additional therapist focus groups in different countries as treatment approaches differ from country to country.

It is also recommended that a full biomechanical study on the ROM and force therapists use while treating their patients be done. In addition, a full biomechanical study of the ROM of the prototype should be done in different configurations with more subjects. These data could then be compared with data on the next revision of the RRD. In addition clinical trials of the device would be necessary to determine its clinical efficacy.
10.5 Closing

RRDs hold promise for making stroke rehabilitation more accessible. Functionality, safety, and usability are key components which must be designed into a RRD, but if the device is not accessible, therapists and their patients will not be able to use it. Accessibility includes cost, ease of use, and portability. Stroke is a chronic disease which requires ongoing rehabilitation. As healthcare costs continue to increase, more and more of this rehabilitation will need to happen at home or in the community. Designing a low cost, easy to use, portable device is no easy task. This research presents therapist requirements which must also be incorporated into a usable device. Many more iterations are needed to design the ideal device. This iteration has produced a lower cost, portable device, a step in the right direction.
References


Appendix A. Online Survey

The Development of an Upper Limb Haptic Robotic Rehabilitation System for Stroke Rehabilitation

Welcome! We are a multi-disciplinary research team headed by Dr. Alex Mihailidis, Associate Professor in the Department of Occupational Science & Occupation Therapy at the University of Toronto in Canada. Our research specializes in creating intelligent assistive devices for people with disabilities, for example stroke survivors with disabilities. If you would like to learn more about us and our research, please visit www.iatsl.org. Our latest project aims to design and build a robotic rehabilitation system for stroke upper-limb rehabilitation. This device is intended to be a tool to help stroke therapists (i.e. occupational therapists, physiotherapists, etc.) in rehabilitating stroke survivors. It is very important to us that the tool is appropriate and useful to both clients and therapists. Therefore, we are looking to gain a better understanding of the how therapists and their clients currently perform upper-limb rehabilitative activities as well as to determine what features of an assistive device would be useful to therapists and clients. To do this, we are inviting stroke therapists in Australia, Canada, the United States, and the United Kingdom to share their experience with us through this research survey. This survey is entirely voluntary and you can quit the survey at any time. This survey is also part of a Master’s degree program. The information gained through this survey will be used to achieve the goal of our project, which is to give stroke therapists a robotic tool they can use to increase opportunities for upper-limb therapy. The survey includes information on therapist demographics, types of assessments, methods of therapy, rehabilitation settings, aims of rehabilitation, tone, facilitation of movement, attitudes toward functional movements, sensory feedback, and attributes of a robotic rehabilitation device. The online survey company that is used has its servers located in Canada. The online survey can be viewed at www.AskItOnline.com/survey/Rehab-Robot. We respect your privacy - any and all answers you give us will remain confidential. This survey is simple to complete and should take about 20 minutes or less of your time. The information collected will remain strictly confidential and will not affect any of the participants’ employment, care or treatment in any way. A code number will be assigned to each participant when they give consent. Direct quotes may be included in the final research paper but neither names nor other potential identifying descriptions (such as place of employment) will be used in any report or publication.

The primary risk associated with Phase One of this study is risk to reputation or embarrassment if the confidentiality of the responses is breached. These risks will be mitigated by securing the information on password protected secure servers located at Toronto Rehabilitation Institute for up to five years. A code number will be assigned to each participant when they give consent. Direct quotes may be included in the final research paper but neither names nor other potential identifying descriptions (such as place of employment) will be used in any report or publication.
Results from this survey will be published in a journal article. If you desire a copy of the results sent to your email, please include your email address at the end of the survey. All email addresses used in the study will be voluntarily provided by the respondents and will remain strictly confidential, and will not be shared or used outside the purpose of dissemination of information regarding the study. Each survey will be given a number and any email addresses will be taken off the survey and kept on a separate list.

If you have any questions or concerns about the survey, please contact any one of the researchers involved: Alex Mihailidis (email: alex.mihailidis@utoronto.ca; phone: 416-946-8565), Elaine Lu (ec.lu@utoronto.ca), Jennifer Boger (jen.boger@utoronto.ca; 416-946-8573), Debbie Hebert (hebert.debbie@torontorehab.on.ca), or Rosalie Wang (wang.rosalie@gmail.com) If you have any questions about your rights as a research participant please contact Dr. Gaetan Tardif, Chair of the Toronto Rehab Research Ethics Board at 416-597-3422 x 3730 or by email at reb@torontorehab.on.ca.

Participating in this survey signifies your informed consent to share your responses with our research team. Contributing to this survey does not entitle you to any profits generated by a successful robotic device or offer you any purchasing advantage. If you decide to participate in this survey, please submit the survey only once.

To continue please check one...

☐ Yes! I would like to participate in this survey   ☐ No, not this time

**Part I: Background and Treatment Approach**

1. What is your profession?
   ☐ Occupational Therapist
   ☐ Physical Therapist
   ☐ Rehabilitation Nurse
   ☐ Other, please specify: ________________________________________________

2. What credential(s) do you hold:
   ☐ BA or BS
   ☐ MSPT, MSOT, MA
   ☐ DPT, DOT, PhD
   ☐ Other, please specify:__________________________________________________

3. What country(s) do you work in?
☐ Australia
☐ Canada
☐ United Kingdom
☐ United States of America
☐ Other, please specify: __________________________________________________________________________

4. What methods of stroke treatment do you practice? Please select all that apply:
   ☐ Neurophysiological/Neurodevelopmental Treatment
   ☐ Constraint-Induced Movement Therapy
   ☐ Proprioceptive Neuromuscular Facilitation (Brunnstrom)
   ☐ Motor Relearning Program
   ☐ Electrical stimulation
   ☐ Robot assisted rehabilitation
   ☐ Joint position biofeedback
   ☐ Electromyographic biofeedback
   ☐ Mental practice with motor imagery
   ☐ Repetitive task training
   ☐ High intensity/practice
   ☐ Splinting or orthosis
   ☐ Other, please specify: _______________________________________________________________________

5. How long have you been working with stroke clients?
   ☐ <1 year
   ☐ 1-5 years
   ☐ 6-10 years
   ☐ >10 years

6. What population(s) do you work with? Please select all that apply:
   ☐ Children (0-10 yrs)
   ☐ Youth (11-18 yrs)
   ☐ Adults (19-64 yrs)
   ☐ Senior Adults (65+ yrs)

7. In what settings have you worked with stroke clients? Please select all that apply:
   ☐ Acute care (inpatient)
   ☐ Rehabilitation hospital
   ☐ Long-term care facilities
   ☐ Outpatient clinic
   ☐ Home care
   ☐ Other, please specify: _______________________________________________________________________


8. What assessment tools do you use to assess the level of impairment, functionality, or disability in the upper limb of stroke clients? Please select all that apply:

- Chedoke-McMaster Stroke Assessment
- Wolf Motor Function Test
- Fugl-Meyer scale
- Action Research Arm Test
- Motor Assessment Scale
- NIH Stroke Scale
- Other, please specify: ___________________________________

**Part 2: Aims of Rehabilitation**

Please select how important you think the following aims of upper limb rehabilitation are:

<table>
<thead>
<tr>
<th>Aims of Rehabilitation</th>
<th>Very Unimportant</th>
<th>Somewhat Unimportant</th>
<th>Neutral</th>
<th>Somewhat Important</th>
<th>Very Important</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Learn normal muscle movement</td>
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<tr>
<td>2. Learn compensational strategies</td>
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<tr>
<td>3. Prevent further injury or complications</td>
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<td>4. Facilitate functional activities</td>
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<td></td>
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<tr>
<td>5. Learn how to isolate muscle activation</td>
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<tr>
<td>6. Restore alignment of the joints</td>
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<tr>
<td>7. Improve coordination</td>
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<td>8. Prevent secondary tissue changes</td>
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</tbody>
</table>

If you have any comments on the above, please include the question number and the comment below:

________________________________________________________________
Part 3: Tone

In clients where high tone or muscle tension is present, select the importance of the following goals of when providing therapy for the upper limb:

<table>
<thead>
<tr>
<th></th>
<th>Very Unimportant</th>
<th>Somewhat Unimportant</th>
<th>Neutral</th>
<th>Somewhat Important</th>
<th>Very Important</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Decreasing tone is important when facilitating movement.</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2.</td>
<td>Functional tasks may improve without changes in tone.</td>
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<tr>
<td>3.</td>
<td>Strategies to move from closed chain to open chain activities.</td>
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<tr>
<td>4.</td>
<td>Movement should be slow for those with high tone.</td>
<td></td>
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</tr>
<tr>
<td>5.</td>
<td>Movement should be graded for those with high tone.</td>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

If you have any comments on the above, please include the question number and the comment below:

________________________________________________________________

Part 4: Facilitation of Movement

Please select how much you agree or disagree with the following statements while performing upper limb therapy:
<table>
<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Stroke survivors need task oriented training and practice.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2.</td>
<td>Stroke survivors need regular one-on-one therapy sessions.</td>
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<tr>
<td>3.</td>
<td>Trunk stability is a prerequisite for quality upper arm movement.</td>
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<tr>
<td>5.</td>
<td>Few high quality movements are more important than many poor quality movements.</td>
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<td></td>
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<tr>
<td>6.</td>
<td>Strength training is important to incorporate in any stroke rehabilitation program.</td>
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<td></td>
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</tr>
<tr>
<td>7.</td>
<td>Stroke survivors need context-specific cognitive learning, feedback, and practice.</td>
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<td></td>
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</tr>
<tr>
<td>8.</td>
<td>Electrical stimulation is a good way to increase muscle movement</td>
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<tr>
<td>9.</td>
<td>Where the potential for recovery of normal movement exists, I would delay performing certain activities if they reinforce abnormal movement patterns.</td>
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<td></td>
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<tr>
<td>10.</td>
<td>Improving a client’s ability to move does not necessarily improve the ability to perform functional tasks.</td>
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<tr>
<td>11.</td>
<td>High intensity of focused therapy will allow the stroke survivor to recover sooner.</td>
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<td></td>
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<tr>
<td>12.</td>
<td>Active motor sequences that are performed repetitively within a single training session with a clear functional goal will aid in recovery of that functional task.</td>
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<tr>
<td>13.</td>
<td>Passive upper limb movement will naturally lead to active upper limb movement.</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Part 5: Sensory Feedback

Please select how much you agree or disagree with the following statements about biofeedback in therapy:

<table>
<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Biofeedback is an important tool to use.</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2. Biofeedback on muscle activation would be a useful tool for me.</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>3. Biofeedback on muscle activated would be a useful tool for the stroke survivor.</td>
<td></td>
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<tr>
<td>4. Biofeedback on joint position would be a useful tool for me.</td>
<td></td>
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<tr>
<td>5. Biofeedback on joint position would be a useful tool for the stroke survivor.</td>
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<td></td>
</tr>
</tbody>
</table>

Upper Limb Robotic Rehabilitation Device

Imagine that you have a device that would enable your clients to perform rehabilitative activities (i.e. reaching motions). The device would be programmable by the therapist and could be used in therapy or at home. This device would be able to alter the resistance the client feels in each activity. It would be attached to a monitor which would provide motivational activities. For the following statements, we would like to learn what features and functions you think would be useful on this device. Select whether you agree or not with each statement.
Part 6: Robotic Rehabilitation Device

The robotic rehabilitation device for the upper limb should...

<table>
<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Be a useful tool for stroke survivors to use at home</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2.</td>
<td>Be a compact device</td>
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<td>3.</td>
<td>Be transportable from a clinic to a home</td>
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<td>4.</td>
<td>Be able to facilitate many arm movements</td>
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<td>5.</td>
<td>Contain modular units with different functions (rehabilitate different movements)</td>
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<tr>
<td>6.</td>
<td>Adjusts resistance based on client performance</td>
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<tr>
<td>7.</td>
<td>Once dispatched, requires little adjustment from therapists</td>
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<tr>
<td>8.</td>
<td>Requires specific adjustment from the therapist to ensure good fit</td>
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<tr>
<td>9.</td>
<td>Allow for movement in the sagittal plane</td>
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<tr>
<td>10.</td>
<td>Allow for movement in the transverse plane</td>
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<tr>
<td>11.</td>
<td>Maintain proper joint alignment</td>
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<tr>
<td>12.</td>
<td>Have a touch-screen</td>
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<td>13.</td>
<td>Have a keyboard and mouse</td>
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<td>14.</td>
<td>Have predefined buttons</td>
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<td>15.</td>
<td>Have separate interfaces for therapists and clients</td>
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</tbody>
</table>

Top 5 attributes

Of the above options (#1 to #15) for the rehabilitation robot rank the top 5 attributes and list them in order:

#1 (most important):___________
Part 6 (continued): Robotic Rehabilitation Device

The robotic device for upper limb rehabilitation should...

<table>
<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Somewhat Disagree</th>
<th>Neutral</th>
<th>Somewhat Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>16. Give biofeedback to the client</td>
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<tr>
<td>17. Give biofeedback to the therapist</td>
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<tr>
<td>18. Have virtual ADL specific activities</td>
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<td>19. Have fun activities that may not necessarily be task specific</td>
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<tr>
<td>20. Be usable in a seated position</td>
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<td>21. Be usable in a standing position</td>
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<tr>
<td>22. Be usable in a recumbent position</td>
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<tr>
<td>23. Provide arm stability</td>
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<tr>
<td>24. Provide hand stability</td>
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<tr>
<td>25. Provide trunk stability</td>
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<tr>
<td>26. Allow different handholds for the hand.</td>
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<tr>
<td>27. Have a flexible handhold</td>
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<tr>
<td>28. Be an exoskeleton that will help control each joint</td>
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<tr>
<td>29. Have a handhold the client would be able to move around</td>
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</tbody>
</table>

Top 5 attributes
Of the above options (#16 to #29) for the rehabilitation robot rank the top 5 attributes and list them in order:

#1 (most important): _________
#2 _________
#3 _________
#4 _________
#5 _________

Usage
Should the device be used only with a therapist or for personal use?

☐ Only with a therapist
☐ Only for personal use
☐ Both with a therapist and at home

Cost
How much do you think you or your clinic/hospital would be willing to pay for an upper limb rehabilitation robot?

☐ <$1000 USD  ☐ $1000 - $5999 USD  ☐ $6000 - $9,999 USD  ☐ $10,000 - $24,999 USD  ☐ $25,000 - $50,000 USD  ☐ >$50,000  ☐ Not interested in purchasing an upper limb rehabilitation robot

Comments
Do you have any comments you would like to share about device features you think would be useful to your stroke clients?

If you would like to be notified of the publication resulting from this study, please enter your email address (below). Your email will be kept confidential and will not be used for any other purpose or shared with any outside parties.

___________________________________________________________

Thank You
Your data was submitted successfully.

Thank you for participating in our survey. Your opinions are important to us and we appreciate your time. If you have any questions or comments, please contact us at iatsl@utoronto.ca If you wish to check on the status of the study, please visit our website at www.iatsl.org
Appendix B. Letter to Organizations

Dear __________,

My name is Elaine Lu and I am a Master's student in Clinical Biomedical Engineering at the University of Toronto. We are doing a study to understand the needs of stroke therapists with regards to creating an upper limb rehabilitation robot for therapist and stroke survivor use.

The overall, long-term goal of this research is to redesign a robotic rehabilitation system for upper limb rehabilitation. We envision a device that is affordable and unobtrusive enough that it would increase opportunities for upper limb rehabilitative therapy while decreasing therapist loads. This study hopes to apply the principles of participatory design to identify features, specifications, and user-interfaces that would be useful and motivating for stroke survivors and easy for therapists to use in rehabilitating upper limbs of post-stroke clients.

The first part of this study involves an international online survey. We were wondering if it would be possible to send this survey out to your members who are involved in stroke rehabilitation and whom have agreed to be contacted for research studies or surveys. In order to protect the privacy of your members, we will send the survey to you and you may forward it to your members. We do not require their email addresses, unless they voluntarily give it in order to receive the results of the survey. The survey can be found at www.askitonline.com/survey/rehab-robot.

Thank you so much for your time,

Sincerely,

Elaine Lu
Appendix C. House of Quality

*Adapted from House of Quality Tutorial: www.webducate.net/qfd/qfd.html. See Figure C-1.

Customer Requirements – use an affinity and tree diagram to group into levels and categories
- Customer statements are written on a separate card
- Cards are arranged in groups with perceived associations
- From each group a title card is chosen which encapsulates the meaning of the group
- Group title cards to higher level associations

Planning Matrix
- Quantifies customer requirements through prioritizing the perception of existing products
- Allows priorities to be adjusted based on design issues
- Weighting amount quantifies the relative importance of each requirement
- Includes:
  - Satisfaction of available products
  - Planned satisfaction for future products
  - An improvement factor (Difference between current and future product)

Technical Requirements – measurable characteristics of the product
- Includes direction for change (increase/decrease)
- Interrelationships
- Translate the requirements as expressed by the customer into technical characteristics of the product
- Determine where the interrelationships are significant
- Each level of interrelationship is assigned a score

Roof
- Technical requirements that support or impede each other

Targets
- Technical priorities, competitive benchmarks,
- Calculated from weightings in planning and interrelationships multiplied by overall weighing
Figure C-1. House of Quality Matrix.
Appendix D. Target Calculations

Workspace and range of motion
These calculations assume that the person is sitting a forearm’s length from the table, see figure D-1:

![Diagram](image)

Figure D-1. Sagittal workspace for a forward reaching motion.

\[
x^2 + y'^2 = (x + y)^2
\]

\[
y'^2 = y^2 + 2xy
\]

\[
y' = y + s
\]

\[
(y + s)^2 = y^2 + 2xy
\]

\[
s = \pm\sqrt{y^2 + 2xy - y}
\]

Using data from the 95\(^{th}\) percentile of US men (taken from two sets of data, one from civilians and one from the U.S. Marine Corps)[100], [101], where \(x\) is the shoulder-elbow length (431 mm)[100] and \(y\) is the forearm length, that is the elbow to fingertip length minus the hand length (520.4 mm - 209.2 mm = 311.2 mm)[101]. The sagittal axis (s) workspace would be:

\[
x = 431 \text{ mm}
\]

\[
y = 520.4 - 209.2 = 311.2 \text{ mm}
\]

\[
s = \pm\sqrt{311.2^2 + 2 \times 431 \times 311.2} - 311.2 = 293 \text{ mm}
\]

For the frontal axis (f), using normal shoulder adduction/abduction (0-90\(^°\)) range of motion [102] while maintaining the hand on the table workspace, see figure D-2:

\[
f = \sqrt{(x + y)^2 - y^2}
\]

\[
f = \sqrt{x^2 + 2xy}
\]
The longitudinal axis would account for the flexion of the shoulder (0-90°) range of motion[102].

\[ f = \sqrt{431^2 + 2 \times 431 \times 311.2} = 673 \text{ mm} \]

Figure D- 2. Frontal axis workspace.

Rotational movement would be limited to the end effector for the 2 DoF robot, as such it would be limited to the wrist and elbow movement.

Pitch movement would include wrist flexion (0-90°) and extension (0-70°), for a total of 160°.

Yaw movement would include wrist abduction (0-25°) and adduction (0-65°), for a total of 90°.

\[ l = \sqrt{(x + y)^2 - y^2} + x \]
\[ l = f + x \]
\[ l = 673 + 431 = 1104 \text{ mm} \]

Figure D- 3. Longitudinal axis workspace
Roll movement would include elbow supination (0-90°) and pronation (0-90°), for a total of 180°.

**Motor force**
According to the Merck manual, the top grade of muscle strength is defined as “Full range of motion against gravity and full resistance for patient’s size, age, and sex.” [102]. This was used to calculate the maximum resistive force needed. The average weight of an arm is 3.216±0.464 [106] kg, therefore the 95th percentile arm would weigh 4.14 kg. The acceleration would be gravity (9.80 m/s²)[108].

\[
F = ma \\
F = 4.14 \times 9.80 = 40.6 \text{ N}
\]

For assistive forces, the maximum acceleration to move a glass and plate was used [99]. This was determined to be 4 m/s². Therefore the assistive force required would be:

\[
F = ma \\
F = 4.14 \times 4.00 = 16.6 \text{ N}
\]

The maximum acceleration can also be taken at 4 m/s².
Resolution is taken from the HapticMaster at 0.012 mm/count, which indicates that the system is able to detect differences as small as 0.012 mm.
Appendix E. Focus Group Discussion Guide

The primary purposes of the focus group(s) are to:

1. Discuss potential uses of robotic technology in upper limb stroke therapy
   a. How technology can augment current practices
   b. Potential uses and needs for technology
2. Determine what features are necessary in an acceptable upper limb stroke rehabilitation device with respect to:
   a. Design and functions of the mechanical device
   b. Usability
   c. Ergonomics
   d. Adjustability
   e. Safety
   f. User interface (both for therapists and stroke survivors)
   g. Types of data collected (e.g. Biofeedback)
3. Determine which items are most important to therapists in terms of
   a. Size
   b. Cost
   c. Range of motion capabilities
   d. Degrees of freedom
   e. Amount of force (assistive and resistive)
4. Brainstorm potential upper limb rehabilitative activities
   a. In a clinic with a therapist
   b. At home
   c. Interactive games – social games

Below are general guidelines for the focus group. Moderators should follow this guide as much as it is possible, but be flexible in leading the discussions. Moderators should aim to at least address in as much detail the purposes outlined above. Participants should also be informed that the focus group is being recorded.

Before the focus group begins, participants should provide informed consent and where appropriate be informed of compensation procedures.

Total Focus Group Length: 60-90 minutes

Discussion Guide:

1. Introduction (~10 minutes)
   a. Welcome participants, make introductions
   b. Gather confidential demographics (see Part I of Appendix A)
   c. Explain the purpose of the focus groups, how it will be run, and expectations from each member
i. Taking turns
ii. Succinct comments are appreciated
iii. All opinions respected, all comments are treated confidentially by the researchers, also ask that they treat the comments confidentially as well. However, the researchers, cannot guarantee that all Focus Group participants will treat the information confidentially, so keep that in mind if there are things you do not want to talk about.
iv. Please ask questions – this may generate discussion from other members

2. Potential uses of robotic devices in upper limb stroke therapy
   a. What kinds of devices have you wished you had while treating the upper limbs of stroke patients?
   b. What kinds of devices have you used in the past which have been helpful? Not so helpful?
   c. If there was a device your client could take home and use for practice, what would this device do?

3. Storyboards, Mockups and Prototypes
   a. Researchers introduce storyboards, mockups, and prototypes
      i. History about the design up to this point
      ii. Participants’ role in furthering design
   a. Have participants go through the storyboards, mockups, prototypes
      i. Have them “think out loud” while interacting with the items
      ii. How they would use the device
      iii. What problems they would encounter
   b. Ask questions to generate discussion such as:
      i. What do you think about the range of motion, is it adequate?
      ii. What do you think about the amount of force?
      iii. Is the device too big/small?
      iv. Are there potential safety issues you can foresee?
      v. Does the device look/feel comfortable?
      vi. How easy is it to use?
         i. Are there any other desired features you would like to see?
         ii. What features do you see as being beneficial?
         iii. What features do you see as being an obstacle to this device’s use?
         iv. Would there be any differences in features you would include in a “home edition” version of the device?
      vi. How do you see this working in your workplace?
   c. What would influence your decision on whether or not you would purchase/use such a device? What factors are more important than others? What tradeoffs would be good/not so good?
      i. Cost
      ii. Size
iii. Functionality – Range of motion, degrees of freedom, force
iv. Type of device
v. Usability

4. As a therapist, what would you like in a user interface?

5. What types of feedback (visual, auditory, tactile, biofeedback) are:
   b. Necessary for the therapist to perform his/her duties
      i. Does the device need to allow for cueing?
      ii. Does the device need to give biofeedback?
      iii. What types of alarms are necessary?
   c. Necessary for the stroke survivor to regain arm functionality?
   d. Other types of data that should be collected?

6. Brainstorm activities for the device
   e. What types of activities could you envision a rehabilitation robot doing? (not limited to the mockups or prototypes presented)
      i. In the clinic
      ii. At home
      iii. Interactively with other stroke survivors or caregivers

7. Closing (5 min)
   f. Thanks and closing remarks
   g. Issue compensation
   h. Ask participants (if they are willing) to inform stroke survivors about the study
Appendix F. Information and Consent Form

Informed Consent to Participate in a Research Study

Study Title: The Development of an Upper Limb Haptic Robotic Rehabilitation System for Stroke Rehabilitation, Phase Two

Principal Investigator: Dr. Alex Mihailidis, Occupational Science and Occupational Therapy (University of Toronto)
Ph: (416) 946-8565
email: alex.mihailidis@utoronto.ca

Researchers:
Elaine Lu, MHSc. Candidate, University of Toronto
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Dr. Rajibul Huq, Post Doctoral Fellow, University of Toronto
Ph: (416) 946-8573
Email: rajibul.huq@gmail.com

Research Coordinator: Jennifer Boger, Research Manager, University of Toronto
Ph: (416) 946-8573
dr: jen.boger@utoronto.ca

Clinical Researcher: Debbie Hebert, Corporate Professional Leader of Occupational Therapy and Clinical Educator for Toronto Rehabilitation Institute
Ph: (416) 597-3422 x 3505
dr: hebert.debbie@torontorehab.on.ca

Informed Consent

You are being invited to participate in a research study that will include stroke therapists in the design of a robotic system that will help in the shoulder and arm rehabilitation of those who have had a stroke.

Please read this form carefully and ask any questions you may have. You may take as much time as you wish to decide whether or not to participate. Please ask the study staff or one of the investigator(s) to clarify anything you do not understand or would like to know more about.
Make sure all your questions are answered to your satisfaction before deciding whether to participate in this research study.
Your participation in this study is voluntary. You may choose to withdraw/not participate in this study at any time without any repercussions on your current or future employment.

Introduction

Rehabilitation of the shoulder, arm, and hand after a stroke is important for daily activities and independence. Currently stroke therapy often requires a therapist to be present and may be limited to therapist availability and location. The researchers ultimately would like a device that would be affordable and small enough to be able to increase opportunities for rehabilitation while at the same time helping stroke therapist with their therapy. The goal of this project is to design a robotic system for shoulder, arm, and hand rehabilitation. This device is intended to be a tool to help stroke therapists (i.e. occupational therapists, physiotherapists, etc.) in helping stroke survivors. It is very important to us that the tool is appropriate and useful to both stroke survivors and therapists, so, we are looking to gain a better understanding of the how therapists and stroke survivors currently exercise the shoulder, arm, and hand, as well as find out what parts of an assistive device would be useful to therapists and stroke survivors.

You are invited to participate in the study because you are a therapist who has experience treating stroke survivors and are familiar with the issues associated with stroke rehabilitation. If you choose to participate, your opinions and information will be used to ensure that the device is safe, effective and useable.

What Will Happen During the Study?

You are invited to participate in a focus group with up to nine other therapists to investigate strategies used for stroke rehabilitation and how these can be incorporated into the design of an upper limb rehabilitation device. The structure of the focus groups is expected to be as follows:

- Introduction – overview of the purpose of the focus group
- Demographic information gathering, which will include profession, credentials, methods of stroke treatment, and length of time working with stroke clients.
- Mockups, storyboards, and possible prototypes will be presented to discuss physical aspects of the device, usability, ergonomics, functions, and safety.
- Closing discussions

Participation in the focus groups is expected to take about an hour to an hour and a half for each session. There will be one session. Focus groups will be conducted in a room at Toronto Rehabilitation Institute and will be videotaped to ensure accurate documentation of the discussions.
Who and How Many People Will Take Part in the Study?

It is anticipated that up to ten therapists and two design team members will participate in this focus group study. The focus groups will be moderated by the Arcus Group, a business consulting firm.

What are the Responsibilities of the Study Participants?

If you decide to participate in this study you will be asked to do the following:

- Carefully read all the information in this package
- Ask any questions you might have about the study
- Sign the consent form
- Be available to attend the focus group session
- Be open and creative

Details to be considered:

All sessions will be videotaped to ensure no details from the sessions are missed. All videotaped data will remain strictly confidential and will only be viewed by the research team. After a period of five years, all video data will be destroyed.

Data from this study will be used in the development of a rehabilitation robotic device only

Sessions will take place at Toronto Rehabilitation Institute

What are the Risks or Harms of Participating in this Study?

There is a time commitment if you participate in this study. We will try to schedule the focus groups at times that are most convenient to the group, and they will be held at Toronto Rehab. If real prototype(s) are used, there may be a risk of discomfort when using the prototype. To minimize this risk, a risk assessment and safety testing will be done on the device(s) before using them in the focus group.

There is also a risk of loss of reputation or embarrassment if the confidentiality of your participation and responses is breached. The research team will treat your responses respectfully and confidentially.

How will confidentiality be maintained?

Information, including recorded videos of the sessions will be secured on password protected secure servers located at Toronto Rehabilitation Institute (200 Elm, Toronto, ON, Canada), which has video surveillance, is card access controlled, and is fireproof. Access will be
restricted to the principal investigator and researchers of this project. Access to the computerized data will be password protected on an institutional network drive which has firewalls, anti-virus software, and system patching. All passwords are changed every 90 days to ensure additional security of all the data stored on the server. All data will be kept for the duration of the study and will be destroyed five years after the study is complete. Jennifer Boger will be in charge of destroying this data after 5 years. If there are physical copies (paper, DVD’s, videotapes), these copies will be shredded or physically broken apart. You will be assigned a code number if you give consent and this will be used on your forms. Only this form will contain your name and personal identifying information. The information and consent form will be stored in a secure, locked area with access exclusively restricted to the research team. Study data will be restricted to the research team. Any analyzed data that is used on any computers will be deleted as soon as the analysis is complete. We may use direct quotes from you in the final research paper, but neither your name nor other potential identifying descriptions will be used in any report or publication.

Since we are gathering data in a focus group form, the other participants will hear your responses. The researchers cannot guarantee that the other focus group participants will treat your responses confidentially. We will ask all focus group participants to treat the information confidentially, to encourage honest and frank discussion, but we cannot enforce this. You should be aware of this limit to confidentiality when deciding whether to participate in the research.

**What are the Benefits of Participating in this Study?**

You may or may not benefit directly from participating in this study. However, possible benefits include learning more about state of the art rehabilitation devices. Your participation will be used to develop a device that may help other therapists and stroke survivors in their rehabilitation. You will not benefit financially from the development of this device.

**Can Participation in this Study End Early?**

You can choose to end your participation at any time, such as declining to answer certain questions during the focus groups, or leaving a focus group early. If you withdraw voluntarily from the study, you are encouraged to contact Jennifer Boger, Research Coordinator at (416) 946-8573 or jen.boger@utoronto.ca to share your experience about the study. You do not have to give a reason for withdrawing from the study, but it may help future studies if you are willing to share.

**What are the Costs of Participating in this Study?**

There are no direct costs to participate in this study. Indirect costs will be minimized by arranging times that would be suitable for the participants.

**Are Study Participants Paid to Participate in this Study?**
If you decide to participate in this study, you will be compensated $40 for your time.

**Do the Investigators Have any Conflicts of Interest?**

There are no conflicts of interest for any of the investigators at this time in this study. None of the research team members have financial interests in the manufacturers of the current therapy devices. However, this information may be used to develop a commercial upper limb stroke rehabilitation device in the future. This study is a part of a Master’s degree program.

**What if I have Further Questions?**

If you have questions about your rights as a research participant, or about any ethical issues relating to this study, you can contact the Chair of the Research Ethics Board at (416) 597-3422 x3081.
Documentation of Informed Consent

Full Study Title: The Development of an Upper Limb Haptic Robotic Rehabilitation System for Stroke Rehabilitation: Phase Two

Participant

By signing this form, I confirm that:

- This research study has been fully explained to me and all of my questions answered to my satisfaction
- I understand the requirements of participating in this research study
- I understand that the research study will be videotaped
- Still photos may be taken for the purposes of scientific papers or presentations, in which case, faces and other identifying features of participants will be blocked
- I have been informed of the risks and benefits, if any, of participating in this research study
- I have been informed of any alternatives to participating in this research study
- I have been informed of the rights of research participants
- I have read each page of this form
- I authorize access to research study data as explained in this form
- I have agreed to participate in this study

_________________________  ________________________  ________________
Name of participant (print)  Signature  Date

Person obtaining consent

By signing this form, I confirm that:

- I have explained this study and its purpose to the participant named above
- I have answered all questions asked by the participant
- I will give a copy of this signed and dated document to the participant

_________________________  ________________________  ________________
Name of person obtaining consent (print)  Signature  Date
Appendix G. Matlab Code for Biomechanics Data

Matlab code to process the biomechanics data

% Processes the Vicon data (CSV format) into Wrist, Elbow, Shoulder angles
% Import the data in one matrix with 5 rows of headers

    clear all
    ID=inputdlg('Enter ID');

    for i=1:14
        if i<10
            file=importdata(strcat('Trial0',num2str(i),'.csv'),',',5);
        else
            file=importdata(strcat('Trial',num2str(i),'.csv'),',',5);
        end

        data=file.data;

    %Create a 4th order low pass Butterworth filter based on 100 Hz sample rate (as per Winter, Biomechanics and Motor Control of Human Movment, 2009), filter raw data, look up frequency cutoffs from fft graphs

        [B,A]=butter(2,.1);  %Cutoff at 5 Hz for most

            C7=filter(B,A,data(:,3:5));
            Clav=filter(B,A,data(:,6:8));
            LSHO=filter(B,A,data(:,9:11));
            RSHO=filter(B,A,data(:,12:14));
            RUPA=filter(B,A,data(:,15:17));
            RELB=filter(B,A,data(:,18:20));
            RFRM=filter(B,A,data(:,21:23));
            RWRA=filter(B,A,data(:,24:26));
            RWRB=filter(B,A,data(:,27:29));
            RFIN=filter(B,A,data(:,30:32));
            LPSI=filter(B,A,data(:,33:35));
            RPSI=filter(B,A,data(:,36:38));
            Time=0.01.*data(:,1);

    % Calculate trunk centers
    TrunkCtr=0.5*(RSHO+LSHO);

165
PSICtr=0.5*(LPSI+RPSI);

% Calculate limb vectors
Wrist=RWRA;                     %Wrist defined by the radial styloid
Hand=(Wrist-RFIN);              %Hand vector points to the fingers
Forearm=(RELB-Wrist);           %Forearm vector points to the elbow
Trunky=(RSHO(:,1:2)-LSHO(:,1:2)); %Trunk vector points to RSHO
Upperarm=RELB-RSHO;            %Upperarm vector points to RSHO
   Uppery(:,1:2)=Upperarm(:,1:2);
   Upperz(:,1)=Upperarm(:,1);
   Upperz(:,2)=Upperarm(:,3);
Trunkz=(PSICtr-TrunkCtr);
Trunkz(:,2)=[ ];

% Calculate angles of body segments - raw data
WAngle=zeros(size(Time));
EAngle=zeros(size(Time));
SAngle=zeros(size(Time));
SFlex=zeros(size(Time));

for n=1:size(Hand,1)
    WAngle(n,1)=atan2(RFIN(n,2)-RWRA(n,2),RWRA(n,1)-RFIN(n,1));
    EAngle(n,1)=atan2(norm(cross(Forearm(n,:),
      Upperarm(n,:))),dot(Forearm(n,:),
      Upperarm(n,:)));
    SFlex(n,1)=acos(dot(Trunkz(n,:),Upperz(n,:))/norm(Trunkz(n,:).*
       norm(Upperz(n,:))));
    SAngle(n,1)=acos(dot(Trunky(n,:),Uppery(n,:))/(norm(Trunky(n,:).*
       norm(Uppery(n,:)))));
end

save(strcat(ID{1},'Vicon',num2str(i)));
 clear all
end

Calibration code courtesy of Karl Zabjek:

% Load calibration matrix
clear all

% Inverted Sensitivity Matrix SN373, SN5074 (FP3 left foot; channel 7-12),
% SN 5075 (FP4 (right foot); channel 13-18) (Please note channels 1-6 are
% SN373, Channels 7-12 are SN5074 and Channels 13-18 are Channels SN5075):
% pathcalibration = ('C:\Data\Technical\Calibration Matrix\');

filecalibration='calibrationmatrix7064.xls';
calib = xlsread(filecalibration);

Filetype=inputdlg('Enter subject initial and type of movement, Reaching or ROM');

for i=0:5;
    filename=strcat(Filetype{1},num2str(i*10),'.lvm');
    A=importdata(filename,'\t',23);
    c=struct2cell(A);
    fpdata=c{1};

    clear c A

    Pbism = importdata('C:\Users\Elaine\Dropbox\Haptic Robot\Biomechanics\Robot Force plate data\Robotbias.csv',',',23);
    c=struct2cell(Pbism);
    fpbiasdata=c{1};

% remove bias from forceplate file

Pbismean=mean(fpbiasdata);

% Define downsample number
DS=10; %fpdata(i,7); % Downsample by a factor of 10 for 100 hz, and 20 for 50 hz
DSoffset=9; %fpdata(i,8); % Offset a downsample - 1, DS=10, DSoffset=9, DS=20, DSoffset=19

Pdown=downsample(fpdata,DS,DSoffset);

% Define Force plate parameters
GF2 = 50; % gain factor for FP3 and FP4

L=length(Pdown);
frame=zeros(L,1);
Fx3=zeros(L,1);
Fy3=zeros(L,1);
Fz3=zeros(L,1);
Mx3=zeros(L,1);
My3=zeros(L,1);
Mz3=zeros(L,1);
resul=zeros(L,29);
P=zeros(L,23);
copfxd3=zeros(L,1);
copfyd3=zeros(L,1);

% for k=1:1:L
for k = 1:L
    % remove bias
    frame(k,1)=k;
P(k,:)=Pdown(k,:)-Pbismean(1,:);
end

%calculate moments and forces including cross talk.

Fx3(k,1)=((P(k,17)).*(calib(1,1).*GF2))+((P(k,18)).*(calib(1,2).*GF2))+((P(k,19)).*(calib(1,3).*GF2))+((P(k,20)).*(calib(1,4).*GF2))+((P(k,21)).*(calib(1,5).*GF2))+((P(k,22)).*(calib(1,6).*GF2));
Fy3(k,1)=((P(k,17)).*(calib(2,1).*GF2))+((P(k,18)).*(calib(2,2).*GF2))+((P(k,19)).*(calib(2,3).*GF2))+((P(k,20)).*(calib(2,4).*GF2))+((P(k,21)).*(calib(2,5).*GF2))+((P(k,22)).*(calib(2,6).*GF2));
Fz3(k,1)=((P(k,17)).*(calib(3,1).*GF2))+((P(k,18)).*(calib(3,2).*GF2))+((P(k,19)).*(calib(3,3).*GF2))+((P(k,20)).*(calib(3,4).*GF2))+((P(k,21)).*(calib(3,5).*GF2))+((P(k,22)).*(calib(3,6).*GF2));
Mx3(k,1)=((P(k,17)).*(calib(4,1).*GF2))+((P(k,18)).*(calib(4,2).*GF2))+((P(k,19)).*(calib(4,3).*GF2))+((P(k,20)).*(calib(4,4).*GF2))+((P(k,21)).*(calib(4,5).*GF2))+((P(k,22)).*(calib(4,6).*GF2));
My3(k,1)=((P(k,17)).*(calib(5,1).*GF2))+((P(k,18)).*(calib(5,2).*GF2))+((P(k,19)).*(calib(5,3).*GF2))+((P(k,20)).*(calib(5,4).*GF2))+((P(k,21)).*(calib(5,5).*GF2))+((P(k,22)).*(calib(5,6).*GF2));
Mz3(k,1)=((P(k,17)).*(calib(6,1).*GF2))+((P(k,18)).*(calib(6,2).*GF2))+((P(k,19)).*(calib(6,3).*GF2))+((P(k,20)).*(calib(6,4).*GF2))+((P(k,21)).*(calib(6,5).*GF2))+((P(k,22)).*(calib(6,6).*GF2));

k;

%AMTI origin system : calculate cop for right and left forceplate with AMTI calculations in mm (convert from meters to millimeters)
copfxd3(k,1)=((My3(k,1))./Fz3(k,1)).*(-1000);
copfyd3(k,1)=((Mx3(k,1))./Fz3(k,1)).*1000;
end

resul(:,1)=frame(:,1);
resul(:,2)=Fx3(:,1);
resul(:,3)=Fy3(:,1);
resul(:,4)=Fz3(:,1);
resul(:,5)=Mx3(:,1);
fresult(:,6)=My3(:,1);
fresult(:,7)=Mz3(:,1);
fresult(:,8)=copfxd3(:,1);
fresult(:,9)=copfyd3(:,1);
fresult(:,26)=Pdown(:,13); % synch channels
fresult(:,27)=Pdown(:,14); % synch channels
fresult(:,28)=Pdown(:,15); % synch channels
fresult(:,29)=Pdown(:,16); % synch channels

%synch channel
filename=strcat(filename,'.xls');
xlswrite(filename,fresult);

clear subjectname subjectpath filename filenamempath filenamesave filenamepathsave A c
fpdata biaspath biasname biasnamempath Pbis c fpbiasdata

clear DS Dsoffset Pdown L frame P

clear A Fx1 Fy1 Fz1 L Mx1 My1 Mz1 P Pdown Pmarkerdata c copfxd copfyd fresult

clear Fx2 Fy2 Fz2 L Mx2 My2 Mz2 copfxd2 copfyd2 subjectnumber subject subjectcalibration

clear Fx3 Fy3 Fz3 Mx3 My3 Mz3 c copfxd3 copfyd3 copfxd3 copfyd3 fresult

clear finalimportdata finalimportbias Pmarkerdata Pdown Pbis d L Pbismean ans i finalsave

Pbisfile finalsavexl

clear i j finalsavexl l initial fresult k kk L frame filenamesavexl finalsavexl2 finalsavexl2

clear subjectnumber trialnumber subjectname subjectpath filename filenamempath filenamesave

filenamepathsave A C fpdata

clear i biaspath biasname biasnamempath Pbis c fpbiasdata Pbismean DS Dsoffset Pdown GF GF2

k L

clear fresult
end

% Data has been already down sampled and calibrated through a calibration
% matrix.

% Processes the force plate data synching with vicon data, output gives
% processed files as well as summary file which contains the force range per
% device setting for Fx,Fy,Fz,Mx,My,Mz, COPx,COPy

% Filter the data using a cutoff frequency of 5 Hz, sampling rate of 100
% Hz

Filetype=inputdlg('Enter subject intial and type of movement,Reaching or ROM');
MaxForce=zeros(6,9);
MaxForce(:,1)=(0:10:50)';

for i=0:10:50
    Sheet1=xlsread(strcat(Filetype{1},num2str(i),'.lvm.xls'));
    synch=find(lt(Sheet1(:,28),0),1,'first'); %synch the data with the vicon data
    Sheet1(1:synch,:)=[];                       %delete data previous to synch

    FP=zeros(size(Sheet1,1),8);
    FPsummary=zeros(5,8);
    [B,A]=butter(2,0.1);

    for n=1:8
        FP(:,n)=filtfilt(B,A,Sheet1(:,n+1));
        FPsummary(1,n)=min(FP(:,n));                  %minimum
        FPsummary(2,n)=mean(FP(:,n));                 %mean
        FPsummary(3,n)=std(FP(:,n));                  %standard deviation
        FPsummary(4,n)=max(FP(:,n));                  %maximum
        FPsummary(5,n)=FPsummary(4,n)-FPsummary(1,n); %range
    end

    save(strcat(Filetype{1},num2str(i)),'FP','FPsummary');

    save(strcat(Filetype{1},num2str(i)),,'FP','FPsummary');

    MaxForce((i/10)+1,2:9)=FPsummary(5,:);    end

    save(strcat(Filetype{1},'range'),'MaxForce');

% Finds the net averaged maximum force

    F=zeros(6,2);
    F(:,1)=(0:10:50)';

    for n=1:6
        F(n,2)=sqrt(MaxForce(n,2).^2+MaxForce(n,3).^2+MaxForce(n,4).^2);
    end

%Finds the local maximum angle peaks and averages them,

%Create empty arrays
    WAngPkm=zeros(6,1);
    EAngPkm=zeros(6,1);
    SAngPkm=zeros(6,1);

SFAngPkm=zeros(6,1);
RangeWristAng=zeros(6,2);
RangeElbowAng=zeros(6,2);
RangeShAng=zeros(6,2);
RangeSFAng=zeros(6,2);

File=inputdlg('Enter subject intial and type of movement,Reaching or ROM');
for a=0:5

    filename=strcat(File{1},num2str(a*10));

    load(filename);

    RangeWristAng(a+1,1)=min(WAngle(100:end,:));
    RangeElbowAng(a+1,1)=min(EAngle(100:end,:));
    RangeShAng(a+1,1)=min(SAngle(100:end,:));
    RangeSFAng(a+1,1)=min(SFlex(100:end,:));
    RangeWristAng(a+1,2)=max(WAngle(100:end,:));
    RangeElbowAng(a+1,2)=max(EAngle(100:end,:));
    RangeShAng(a+1,2)=max(SAngle(100:end,:));
    RangeSFAng(a+1,2)=max(SFlex(100:end,:));

    WAngPk=findpeaks(WAngle); %Wrist angle peaks
    WAngPkm(a+1,2)=mean(WAngPk);
    EAngPk=findpeaks(EAngle); %Elbow angle peaks
    EAngPkm(a+1,2)=mean( EAngPk);
    SAngPk=findpeaks(SAngle); %Shoulder angle peaks
    SAngPkm(a+1,2)=mean(SAngPk);
end

RangeWristAng(any(isnan(RangeWristAng),2),:)=[]; % Edit out all NaNs
RangeElbowAng(any(isnan(RangeElbowAng),2),:)=[]; % Edit out all NaNs
RangeSFAng(any(isnan(RangeSFAng),2),:)=[]; % Edit out all NaNs

WristRange=[mean(RangeWristAng(:,1)),std(RangeWristAng(:,1)), ...
mean(RangeWristAng(:,2)),std(RangeWristAng(:,2))];

ElbowRange=[mean(RangeElbowAng(:,1)),std(RangeElbowAng(:,1)), ...
mean(RangeElbowAng(:,2)),std(RangeElbowAng(:,2))];
ShPlaneElev=[mean(RangeShAng(:,1)), std(RangeShAng(:,1)), mean(RangeShAng(:,2)), ...
               std(RangeShAng(:,2))];

ShAngleElev=[mean(RangeSFAng(:,1)), std(RangeSFAng(:,1)), mean(RangeSFAng(:,2))...
             , std(RangeSFAng(:,2))];

clear A B EAngPk EAngPkm EAngle ID LPSI LSHO RELB RFIN RPSI RSHO RWRA SAngPk SAngPkm
SAngle SFANgPkm SFlex
clear Time WAngPk WAngPkm WAngle a i n
save(strcat(File{1},'range'));

%Calculate the forces and moments on the wrist, elbow and shoulder joints
%using the calibrated, filtered, and synched data from Vicon and the force
%plate

info=inputdlg({'Subject ID','Type of movement','Body mass (kg)'});
ID=info(1);
Mvmt=info(2);
BodyMass=str2double(info{3});

ViconData=strcat(strcat('C:\Users\Elaine\Dropbox\Haptic Robot\Biomechanics\Vicon
Data\',ID{1},'\'));

ForceData=strcat('C:\Users\Elaine\Dropbox\Haptic Robot\Biomechanics\Robot Force plate
data\',ID{1});

Frequency=100;
t=1/Frequency; %time difference

for i=0:10:50 %batch process all trials for movement type
    %load vicon data
    cd(ViconData);
    filename=strcat(ID{1},'Vicon', Mvmt{1}, num2str(i),'\','mat');
    load(filename,'RFIN', 'RWRA', 'RELB', 'RPSI', 'A', 'B');

    %Filter the data, use only the x,y data assuming all movement is in
    %the xy plane (transverse plane)
    Finger=filter(B,A,RFIN);
Finger(:,3)=[];
Wrist=filter(B,A, RWRA);
Wrist(:,3)=[];
Elbow=filter(B,A, RELB);
Elbow(:,3)=[];
Shoulder=filter(B,A, RSHO);
Shoulder(:,3)=[];

%load force plate data
load (filename, 'FP');
FP((size(RFIN,1)+1):end,:)=[];  %truncate the force plate data

%Calculate using anthropometric data from Winter (2009) Biomechanics
%and motor control of human movement

%Hand
Mhand=0.006.*BodyMass;
Lhand=(sqrt((Wrist(:,1)-Finger(:,1)).^2+(Wrist(:,2)-Finger(:,2)).^2))./1000; %in m
COMhand=Wrist-(0.506.*[(Wrist(:,1)-Finger(:,1)) (Wrist(:,2)-...Finger(:,2))]);    %COM of the hand
Rhohand=0.297.*Lhand;     %rho - radius of gyration
Ihand=Mhand.*Rhohand.^2;  %I - moment of inertia of the hand

%Forearm
Mfa=0.016*BodyMass;
Lfa=(sqrt((Wrist(:,1)-Elbow(:,1)).^2+(Wrist(:,2)-Elbow(:,2)).^2))./1000; %in m
COMfa=Elbow - (0.430.*[(Elbow(:,1)-Wrist(:,1)) (Elbow(:,2)-...Wrist(:,2))]); %COM of the forearm
Rhofa=0.303.*Lfa; %radius of gyration of the forearm
Ifa=Mfa.*Rhofa.^2; %moment of inertia of the forearm

%Upper arm
Mua=0.028*BodyMass;
Lua=(sqrt((Shoulder(:,1)-Elbow(:,1)).^2+(Shoulder(:,2)-...Elbow(:,2))).^2))./1000; %in m
COMua=Shoulder - (0.436.*[(Shoulder(:,1)-Elbow(:,1)) ... (Shoulder(:,2)-Elbow(:,2))]); %COM of the upper arm
Rhoua=0.322.*Lua; %radius of gyration of the upper arm
lua=Mua.*Rhoua.^2;  %moment of inertia of the upper arm

%Calculate angle, angular acceleration, and acceleration of the wrist
Ah=zeros(size(Finger));            %acceleration of the COM of hand
thetaw=zeros(size(Finger(:,1)));    %angle of the wrist
alphaw=zeros(size(Finger(:,1)));    %angular acceleration of wrist

for n=2:(size(Finger(:,1))-1)
    Ah(n,:)=((COMhand(n+1,:)-2.*COMhand(n,:)+COMhand(n-1,:))./(t^2))./1000;
    thetaw(n,1)=atan2(Wrist(n,2)-Finger(n,2), Wrist(n,1)-Finger(n,1)); end

for n=3:(size(Finger(:,1))-2)
    alphaw(n,1)=(thetaw(n+1,1)-2.*thetaw(n,1)+thetaw(n-1,1))./(t^2); end

%Calculate forces and moments at the wrist
Fw(:,1)=(Mhand.*Ah(:,1))-FP(:,1);  %force along x axis
Fw(:,2)=(Mhand.*Ah(:,2))-FP(:,2);  %force along y axis

Mw=FP(:,6) - FP(:,1).*abs(COMhand(:,2)-Finger(:,2))./1000 + ...
     FP(:,2).*abs(COMhand(:,1)-Finger(:,1))./1000 ... 
     -Fw(:,1).*abs(Wrist(:,2)-COMhand(:,2))./1000 + ...
     Fw(:,2).*abs(Wrist(:,1)-COMhand(:,1))./1000-(Ihand.*alphaw);

%Calculate angle, angular acceleration, and acceleration of the elbow
Afa=zeros(size(Finger));            %acceleration of the forearm
thetae=zeros(size(Finger(:,1)));    %angle of the elbow
alphae=zeros(size(Finger(:,1)));    %angular acceleration of elbow

for n=2:(size(Finger(:,1))-1)
    Afa(n,:)=((COMfa(n+1,:)-2.*COMfa(n,:)+COMfa(n-1,:))./(t^2))/1000;
    thetae(n,1)=atan2(Elbow(n,2)-Wrist(n,2),Elbow(n,1)-Wrist(n,1)); end

for n=3:(size(Finger(:,1))-2)
    alphae(n,1)=(thetae(n+1,1)-2.*thetae(n,1)+thetae(n-1,1))./(t^2); end
%Calculate forces and moments at the elbow

\[ Fe(:,1) = (Mfa.*Afa(:,1)) + Fw(:,1) \]  %force along x axis
\[ Fe(:,2) = (Mfa.*Afa(:,2)) + Fw(:,2) \]  %force along y axis

\[ Me = Mw + Fw(:,1).*abs(COMfa(:,2) - Wrist(:,2))./1000 + ... + Fe(:,1).*abs(Elbow(:,2)-COMfa(:,2))./1000 + ... + Fe(:,2).*abs(Elbow(:,1)-COMfa(:,1))./1000 - (Ifa.*alphae); \]

%Calculate angle, angular acceleration, and acceleration of the shoulder

\[ Aua = zeros(size(Finger)); \]  %acceleration of the upper arm
\[ thetas = zeros(size(Finger(:,1))); \]  %angle of the shoulder
\[ alphas = zeros(size(Finger(:,1))); \]  %angular acceleration of the shoulder

for n=2:(size(Finger(:,1))-1)
    Aua(n,:)=(((COMua(n+1,:)-2.*COMua(n,:)+COMua(n-1,:))./(.01).^2))./1000;
    thetas(n,1)=atan2(Shoulder(n,2)-Elbow(n,2), Shoulder(n,1)-Elbow(n,1));
end

for n=3:(size(Finger(:,1))-2)
    alphas(n,1)=(thetas(n+1,1)-2.*thetas(n,1)+thetas(n-1,1))./(t.^2);
end

%Calculate forces and moments at the shoulder

\[ Fs(:,1) = (Mua.*Aua(:,1)) + Fe(:,1) \]  %force along x axis
\[ Fs(:,2) = (Mua.*Aua(:,2)) + Fe(:,2) \]  %force along y axis

\[ Ms = Me + Fe(:,1).*abs(COMua(:,2)-Elbow(:,2))./1000 + ... + Fs(:,1).*abs(Shoulder(:,2)-COMua(:,2))./1000 + ... + Fs(:,2).*abs(Shoulder(:,1)-COMua(:,1))./1000 - (lua.*alphas); \]

%Take out initial noise – visually inspect for initial noise

\[ Fs(1:100,:)=[]; \]
Fe(1:100, :) = []; 
Fw(1:100, :) = []; 
Me(1:100, :) = []; 
Ms(1:100, :) = []; 
Mw(1:100, :) = []; 

save(strcat(ID{1}, Mvmt{1}, 'Moment', num2str(i)), 'Fw', 'Mw', 'Fe', 'Me', 'Fs', 'Ms');
clear Fw Mw Ah thetaw alphaw lua Rhoua COMua Lua Mua Ifa Rhofa COMfa Lfa Mfa 
clear Ihand Rhohand COMhand Lhand Mhand 
clear Finger Wrist Elbow Shoulder Forearm Upperarm Hand FP 
clear Fs Ms Aua thetas alphas 
clear Fe Me Afa thetae alphas 
clear A B RELB RFIN RSHO RWRA n 
end 
clear BodyMass ForceData ViconData filename i info t Frequency 

MSummary = zeros(6,7); 
FSummary = zeros(6,13); 

for n = 1:6 
    load(strcat(ID{1}, Mvmt{1}, 'Moment', num2str((n-1)*10'])); 
    MSummary(n,1) = (n-1)*10; 
    MSummary(n,2) = min(Mw); % minimum 
    MSummary(n,3) = max(Mw); % maximum 
    MSummary(n,4) = min(Me); % minimum 
    MSummary(n,5) = max(Me); % maximum 
    MSummary(n,6) = min(Ms); % minimum 
    MSummary(n,7) = max(Ms); % maximum 
    FSummary(n,1) = (n-1)*10; 
    FSummary(n,2) = min(Fw(:,1)); % minimum 
    FSummary(n,3) = max(Fw(:,1)); % maximum 
    FSummary(n,4) = min(Fw(:,2)); % minimum 
    FSummary(n,5) = max(Fw(:,2)); % maximum 
    FSummary(n,6) = min(Fe(:,1)); % minimum 
    FSummary(n,7) = max(Fe(:,1)); % maximum
FSummary(n,8) = min((Fe(:,2))); % minimum
FSummary(n,9) = max((Fe(:,2))); % maximum

FSummary(n,10) = min((Fs(:,1))); % minimum
FSummary(n,11) = max((Fs(:,1))); % maximum

FSummary(n,12) = min((Fs(:,2))); % minimum
FSummary(n,13) = max((Fs(:,2))); % maximum

FSummary(n,10) = FSummary(n,9) - FSummary(n,8); % range
end

FSummary(7,:) = min(FSummary(1:6,:));
FSummary(8,:) = max(FSummary(1:6,:));

save(strcat(ID{1},Mvmt{1},'ForceSummary'));
clear n Mw Ms Me Fw_mag Fw Fs_mag Fs Fe_mag Fe
Appendix H. Biomechanics Data for Subjects 2, 3, and 4

Note: Subject 2 had too many data points missing from trials 0 Ns/m, 10 Ns/m, 40 Ns/m and 50 Ns/m. The moments could only be calculated for 20 Ns/m and 30 Ns/m for the transverse reaching task and 20 Ns/m, 30 Ns/m, and 40 Ns/m for the sagittal reaching task.

Figure H-1 Sagittal reaching maximum forces and moments on the arm joints, subject 2
Figure H-2 Transverse reaching maximum forces and moments on the arm joints, subject 2
Figure H-3 Sagittal reaching maximum forces and moments on the arm joints, subject 3
Figure H-4 Transverse reaching maximum forces and moments on the arm joints, participant 3
Figure H-5. Sagittal reaching maximum forces and moments on the arm joints, subject 4
Figure H-6. Transverse reaching maximum forces and moments on the arm joints, subject 4
Appendix I. Extended Link Arm Calculation

Using:

- Forearm = the length of the longest forearm in the study: 30 cm (participant 1)
- $2\theta =$ difference between the reference angle and the measured angle (participant 1) for transverse reaching: $2.88 \text{ rad} - 2.12 \text{ rad} = 0.76 \text{ rad}$

\[
\frac{1}{2} x = \text{Forearm} \times \sin \theta
\]

\[
x = 2 \times 30cm \times \sin \left( \frac{0.76}{2} \right)
\]

\[
x = 22 \text{ cm}
\]
Appendix J. Related Publications


Role in paper: designed survey, wrote ethics application for Canada, distributed survey, collected data, analyzed data, wrote first draft of paper.


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