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Development of a robotic device for upper limb stroke rehabilitation: A user-centered design approach

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Abstract

Stroke is one of the major causes of permanent adult disability. Stroke frequently affects motor control of the arm, leading to difficulties in doing activities of daily living. This research focuses on developing an upper limb rehabilitation robotic prototype through user-centered design to aid stroke survivors in rehabilitating their arm. To gather requirements from end users, stroke therapy sessions were observed and a survey of stroke therapists was conducted. End user requirements were evaluated to determine technical targets for the mechanical design of the prototype. Evaluation of the prototype was done with stroke therapists in a focus group and a preliminary biomechanical study. As user-centered design would require more iterations of design, testing and evaluation, this project reports a first step in developing an affordable, portable device, which could increase access to stroke rehabilitation for the arm.

Keywords

stroke · rehabilitation · upper limb · therapeutic · robots · user-centered design

1. Introduction

Worldwide, there are 64.5 million people who live with disability and need assistance for activities of daily living (ADL) due to a stroke [1]. Many hours of therapy are spent on motor rehabilitation to help stroke survivors live more independently. Repetitive activities, such as those that occur during therapy, strengthen motor neural pathways to enable recovery of the limbs for the stroke survivor, making access to stroke rehabilitation critical for maximum recovery [2]. However in many places such as in Canada, stroke rehabilitation services are believed to be inadequate due to a limited number of facilities, lack of funding, and a shortage of qualified staff [3]. These issues could decrease the frequency and duration of a stroke survivor's therapy.

Rehabilitation robots are being developed to aid therapists and increase access to rehabilitation by opening opportunities for rehabilitation and potentially decreasing associated costs. Rehabilitation robotic devices (RRD) are able to offer enriched activity even for those with low functioning limbs. Robotic devices are able to work with stroke survivors, even those with severe impairments, to repetitively assist arm movement, giving the brain repetitive input to aid in re-forming lost neuronal connections.

Studies on RRDs have shown comparative improvement in stroke survivor upper limb outcomes when evaluated against conventional therapy [4–6]. Robots are able to include features such as exact repeti-

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tive movement, adjustable resistance, objective evaluation, and motion sensing capability, which can be used to supplement traditional therapy. Robots will likely never replace therapists, but could be used in assisting therapists or allowing rehabilitation in remote locations or in the home. End effector devices such as the MIT-Manus/InMotion2 [7, 8] and exoskeleton type devices such as the T-WREX/ ArmeoSpring [9] have been developed and studied. Although many devices are being developed [6], only a small percentage of therapists actually use robotic therapy [10]. There may be many hindrances to using robotic therapy, which include insufficient clinical evidence, limited functionality, cost constraints, safety concerns, equipment size, or usability issues [11]. Understanding the end user perspective is pivotal in the design and implementation of RRDs to ensure that they are appropriate and meet end user needs. This paper presents the use of a user-centered design approach to develop a working prototype of a novel low cost RRD for aiding the paretic upper limb.

2. Development of the Robot Prototype

In order to design an appropriate RRD, it is important to understand how therapists treat the paretic arm. The development of an acceptable, usable system requires the end users' input throughout the design process. User-centered design (UCD) is a technique that focuses on the users' needs and designs according to these needs [12, 13]. UCD is an iterative process, which includes the following key principles (adapted from [14]):

- Work practices of the user control development.
- Representative end users 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 aid in visualize and evaluate ideas.
- The development process should be performed by interdisciplinary teams.

The development of the robotic prototype was accomplished through three phases that incorporated the UCD approach:

Phase 1: Identification of Requirements was accomplished through observations of therapists performing stroke rehabilitation and the development, deployment, and analysis of an international therapist survey.

Phase 2: Design and Construction of the Prototype using a House of Quality matrix [15] that was based on the information gathered in Phase 1.

Phase 3: Prototype Evaluation through a focus group with therapists and a preliminary biomechanical analysis with healthy subjects.

Stages involving external research subjects received ethical approval from University of Toronto and Toronto Rehabilitation Institute's Research Ethics Boards.

2.1. Phase 1: Identification of Requirements

2.1.1. Stroke Therapy Observations

Informal observational sessions and interviews were conducted with therapists working at a large rehabilitation hospital in Toronto, Canada. Therapists were purposefully selected because they worked in the area of upper limb post-stroke rehabilitation. Therapy sessions were observed to understand therapists' work processes, their workplace, as well as stroke survivor needs in rehabilitation. Results of these observations informed the internet-based survey that is described in the following section.
Four observational sessions of approximately four hours with five stroke therapists and eight stroke survivors were conducted to understand of therapists' interaction with stroke survivors and the therapists' workflow. Therapists were all occupational therapists (OTs) treating stroke survivors' upper limbs. Therapists were interviewed before or after the observation session. The sessions were not video recorded; written notes were taken while therapists interacted with their patients. Before each session, permission was obtained from the patient prior to observing their treatment. More details of the observation sessions are presented in [16]. Several observations were made and therapists were noted to:

- Work in a limited and shared workspace, for example one large room with several therapy sessions occurring at once
- Physically cue their patients to understand which muscles they were activating
- Instruct their patients to move in different planes of motion
- Incorporate everyday objects such as utensils into their therapy activities
- Have a limited amount of time with their patients, sessions observed were 30 minutes in length
- Provide cognitive rehabilitation activities such as putting a puzzle or model together
- Have concern that their patients were not telling them their true levels of pain

Stroke survivors were observed to have special needs, which would need to be incorporated into the RRD. Examples of patient needs are as follows:

- Many were easily fatigued after a period of activity less than the therapy time
- Many had paretic arms with either low or high tone
- The paretic arm was often very weak, often not being able to grasp objects
- Often there were motor coordination difficulties
- Some stroke survivors had bodily neglect or inattention

These observations suggest several RRD design factors:

- Small and portable
- Easy and quick to set up
- Could be used while a therapist is physically cueing their patient

- Usable in more than one plane
- Incorporates use of everyday objects used in ADLs or could incorporate use of virtual objects
- Include cognitive activities
- Pain detection
- Monitor general muscle fatigue
- Different types of end effectors to position the hand for those with low or high tone
- Could have straps to secure the hand on an end effector
- Aid the stroke survivor with bodily neglect by bringing attention to that side through vibration or audiovisual cues
- Assist movement for very paretic arms
- Use haptic and visual feedback in a virtual reality environment

2.1.2. Internet-based International Therapist Survey

An international therapist survey was developed, distributed, and analyzed to gain a global understanding of current stroke therapist practice in treating the paretic upper limb and to gather therapist requirements for an upper limb RRD [10]. Two hundred and thirty three (233) of the returned surveys were considered to be complete and were analyzed with descriptive statistics. A brief summary of the findings are reported here, and full details of the survey are found in [10, 17].
The survey found that the most commonly used methods for treating the affected upper limbs of stroke survivors were ranked as:

- Repetitive task training
- Motor relearning
- Neurodevelopmental treatment

Of note, only 6% of those surveyed had used robotic therapy in the past. Rated important for aims of rehabilitation were:

- Facilitating functional activities
- Preventing further injury or complications
- Improving coordination
- Preventing secondary tissue changes
- Learning normal muscle movement

Statements rated important for facilitation of movement results included:

- “Stroke survivors need task oriented training and practice”
- “Stroke survivors need context-specific cognitive learning, feedback, and practice”
- “Trunk stability is a prerequisite for quality upper arm movement.”

A majority (50%) included these attributes for an upper limb RRD in their top five list (more than five are included as respondents could choose up to five options):

- “Be able to facilitate many arm movements”
- “Be usable in a seated position”
- “Give biofeedback to the client”
- “Have virtual ADL specific activities”
- “Be a useful tool for stroke patients to use at home”
- “Adjusts resistance based on client performance”
- “Contain modular units with different functions”
- “Maintain proper joint alignment”

Respondents did not feel as strongly with regard to the tone and sensory biofeedback sections, however most agreed that biofeedback would be useful and decreasing tone was somewhat important. A vast majority of respondents (93%) would like a RRD that would be useful both with a therapist and for personal use at home. When asked about how much they or their hospital or clinic would pay for such a device, 74% who responded felt that they were willing to pay below $6000 USD. Only 9% of respondents were not interested in purchasing a RRD for any price.

2.2. Phase 2: Design and Construction of the Prototype

2.2.1. Prototype Design with the House of Quality

The prototype was designed using data gathered in Phase 1. Information from the survey was put into a House of Quality matrix, which is a tool that can be used to connect customer requirements to technical specifications and prioritize technical targets [15]. The House of Quality is used in Quality Function Deployment, a method developed in Japan in the 1960’s and 70’s [18]. It has been successfully used to develop such items as consumer electronics, appliances, clothing, and automobiles [19]. As user-centered design seeks to integrate customer requirements (i.e. user requirements) into its development, the tool was a good fit with user-centered design. The house of quality consists of several components: customer requirements, a planning matrix, technical components, a technical component interaction matrix, an inter-relational matrix, and calculated targets [15].
Customer requirements were categorized according to similar characteristics and given a point value related to the survey results. Technical requirements were generated in consultation with the Quanser Consulting (Markham, ON, Canada; www.quanser.com). The planning matrix used the constraints of the manufacturer and did not compare competitors’ products as only 6% of therapists surveyed had used robotic therapy. Technical priorities (target priorities) were calculated using an interrelationship matrix based on how strong the correlations were between the customer requirements and the technical requirements. Targets were calculated using the 95th percentile of anthropometric data [20, 21], normal values for the range of motion (ROM) and strength in rehabilitation [22]. Portability was calculated using airplane carry on sizes and safe lifting standards [23, 24]. The full House of Quality results and targets may be found in [16].

2.2.2. Robot Prototype Design

This RRD, shown in Figure 1, was intended to aid the affected upper limb of an individual who had suffered a stroke. The device was meant to be used as an aid in increasing ROM, improving hand eye coordination, and strengthening the affected muscles through repetitive motion. In addition, it could be used with a qualified stroke therapist

to aid in the quantitative evaluation with respect to ROM, coordination, and strength. The device was intended to give haptic feedback to the user through DC motors and was able to assist or resist motion depending on the mode selected. The mechanical portion of the robot

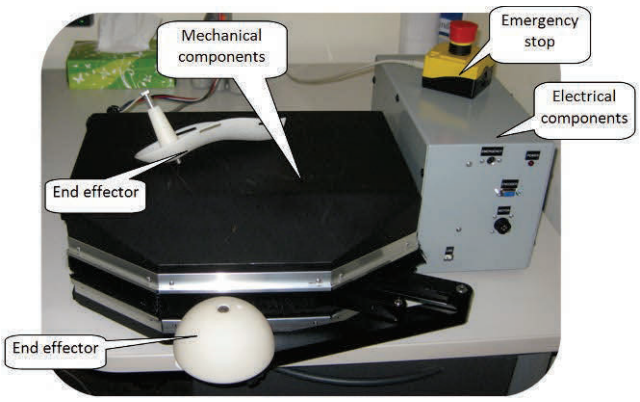

Figure 1. *Rehabilitation robotic device prototype*

was designed in SolidWorks (Concord, MA, www.solidworks.com). It was determined that impedance control would be more suitable than admittance control as the device needed to be low cost, have low inertia, be safe to use, and be backdrivable [25]. Therapists surveyed indicated that they wanted the device to do many things as well as being low cost. The actual design had several trade-offs. As there had been a well studied two degree of freedom (DoF) device with results comparable to usual therapy in the literature [8], it was determined that a two DoF device would be a good starting point to contain costs. Two motors with two optical encoders were used to drive the device. The motors were rated at 110 mN-m of continuous torque. These motors were chosen as they had low inertia and low friction as impedance controlled haptic devices. As the necessary amount of torque was higher than the motors could produce, this torque was increased by using a capstan and capstan way with a 1:30 size ratio. The result was 13.2 N of continuous force per plane of motion at the home position. The resulting resolution (how sensitive the device was in detecting changes in space) was 0.013 mm/count or 76 counts per mm at home position. The forward kinematic model (FKM) of the robot is described using the two link manipulator model shown in Figure 2, where the arm (link) lengths are defined as L_1=254 mm and L_2=266.7 mm. The link angles with x-axis are defined as θ_1 and θ_2. The geometric design criteria of the robot body imposed the following constraints on θ_1 and θ_2.

$$\theta_1 > \theta_2 \quad (1)$$

$$140^\circ \geq \theta_1 - \theta_2 \geq 40^\circ \quad (2)$$

$$90^\circ \geq \theta_1 \geq -50^\circ \quad (3)$$

$$50^\circ \geq \theta_1 \geq -90^\circ \quad (4)$$

Eqns. 5-6 describe the FKM of the robot and Eqn. 7 shows the Jacobean matrix.

$$x = L_1 \cos\theta_1 + L_2 \cos\theta_2 \quad (5)$$

$$y = L_1 \sin\theta_1 + L_2 \sin\theta_2 \quad (6)$$

$$J = \begin{bmatrix} -L_1 \sin\theta_1 & -L_2 \sin\theta_2 \\ -L_1 \cos\theta_1 & -L_2 \cos\theta_2 \end{bmatrix} \quad (7)$$

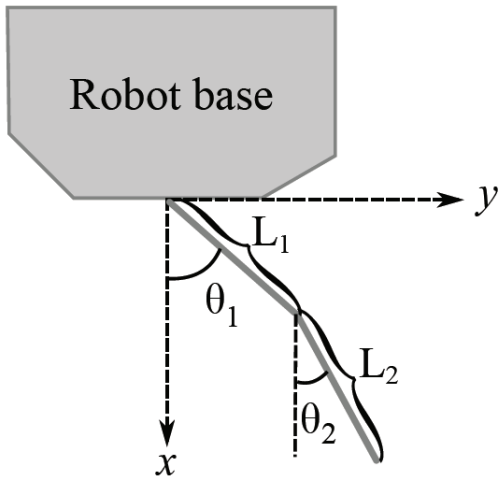

Figure 2. *Two link manipulator model of the robot*

The kinematic equations result in the robot workspace shown in Figure 3. The haptic effect is applied using Eqn. 8, where the force, $F = [F_x \; F_y]^T$ to be applied on the end-effector is converted into torque, $\tau = [\tau_x \; \tau_y]^T$ and then the corresponding current, $I = [I_x \; I_y]^T$ is applied on the motors. The torque amplifying factor of the capstan is denoted as K_a=30 and the torque constant of the motor is found K_t=0.115 N-m/A from the motor specification.

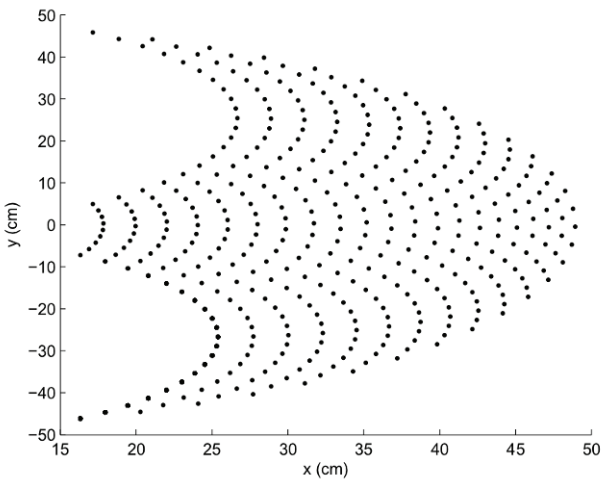

Figure 3. *The workspace of the robot*

$$\tau = -J^T F \quad (8)$$

$$I = \frac{\tau}{K_a K_t} \quad (9)$$

Prototype specifications can be found in Table 1. The prototype con-

Table 1. Prototype target specifications and manufactured specifications

Specification	Target	Manufactured Prototype
Medial/lateral axis	673 mm	931 mm
Anterior/Posterior Axis	293 mm	350 mm
Superior/Inferior Axis	1104 mm	931 mm
Resistive force	40.6 N	52.8 N/plane
Assistive force	16.6 N	52.8 N/plane
Resolution	0.012 mm/ct	0.013 mm/ct
Length	400 mm	320 mm + 180 mm
Width	230 mm	140 mm +155 mm
Height	550 mm	390 mm + 305 mm
Weight	10 kg	17.3 kg
Links	4	4
Joints	3-4	3
End effectors	Modular	2 end effectors
Power	48V @5.2A	48V @5.2A
Sensors	Haptic,joint, pain	Haptic-optical
Actuators	DC motors	DC motors
Computer Compatibility	USB	USB

sisted of three main components: The mechanical portion, the electrical portion, and the computer portion. For this prototype, the electrical and mechanical components were housed separately due to safety reasons. The mechanical components consisted of: an aluminum casing housing a capstan with two DC motors and two optical encoders connected directly to the motors. The internal motors were attached to two aluminum links, which were in turn attached to an aluminum passive arm, and an aluminum outer arm. The outer arm was then attached to a plastic end-effector on a caster wheel. The end effector piece was made to be interchangeable depending on the needs of the stroke survivor. The mechanical part had rubber feet on the bottom, which was used to prevent the case from slipping. The device was meant to be usable in two different planes, the transverse plane and the sagittal plane depending on the orientation of the device.

The electrical portion consisted of: a steel electronics housing, two heat sinks, a fan, three fuses, three circuit boards, and four power modules. An external emergency stop was connected to the device through a cable, which would be used as an emergency shut off for safety purposes. The mechanical portion was connected to the electrical portion through two cables: a motor cable and a sensor cable. The electrical portion was then connected to a computer through a USB cable, and to an AC power source via a standard power cord.

The robot interfaces with a computer through a USB cord. Its software interface included two components: driver and application software. The driver software was developed with QuaRC (Quanser's Rapid Control Prototyping software, www.quanser.com/QUARC) in a MATLAB Simulink environment. The driver software used Quanser's data acquisition card, called Q8, to control the robot. The application software of the robot could be developed using other computer programming languages, e.g., Java and C++. The driver and application software communicate through TCP/IP and shared memory protocol. Currently we are developing a graphical user interface (GUI) in Java as an application software that includes a haptic control interface and virtual reality (VR) games for different upper limb therapy.

3. Phase 3: Prototype Evaluation

The prototype was evaluated with a focus group and with a preliminary biomechanical study. The information gathered from the prototype evaluation will be used to feed into the next cycle of development.

3.1. Focus group

A focus group was conducted to refine the features, specifications, and user interfaces of the upper limb RRD. The focus group consisted of seven therapists (three physiotherapists and four occupational therapists) who had at least two years of experience in stroke therapy, members of the device design team, as well as an external moderator.
Data collected from the therapist survey were analyzed to develop strategic questions for the focus group sessions. The therapists were asked about their satisfaction with current therapeutic technology for stroke survivors and the prototype RRD was presented for critique and input. A more detailed description of the focus group can be found in [16].

3.1.1. Current technology and stroke therapy

When therapists discussed their satisfaction with current technology for stroke upper limb rehabilitation, it was found they had a low level of satisfaction, with an average rating of 3.8±1.0 out of a possible 10 (10 being most satisfied). It was felt that current tools could be used for patients with higher levels of upper limb functioning but there was a lack of devices for lower functioning patients. None of the therapists used any robotic devices for upper limb treatment post brain injury or stroke; however if there was something appropriate, therapists said they would be willing to use technology. Many felt they had not "landed on the right tools yet" and felt there was potential to use more tools. They found the set up of current devices to be time intensive and challenging thereby limiting the amount of time they spent with their patients.
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 in demonstrated effectiveness and measurable changes to the patient's condition. 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 assessment was felt to be highly subjective and lacked quantitative measures.

3.1.2. Current prototype critique

When therapists were shown the prototype of the rehabilitation robot they took turns using the device. 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. Table 2 shows the average ratings therapists gave when asked about the current prototype. Some therapists felt that the main beneficial feature of the device was adequate resistive and assistive forces. When asked whether they would choose a device that had

Table 2. Prototype critique, average of 7 therapists' answers

Component evaluation	Average rating
ROM	4.6±1.0 (10 being most satisfied)
Force	7.5±0.6 (10 being most satisfied)
Setup/Ease of use	4.3±1.2 (10 being most satisfied)
Size	10±0.0 (10 being too large)

more degrees of freedom over a planar device that could assist, they would choose a device that could assist. It was felt that aiding their patients to get movement started was very difficult, but once they had movement there were many more therapy options available.
Therapists were concerned the device would be difficult to setup, especially in terms of the patients having the correct body position. There was also concern about the electrical wiring between the electrical and mechanical cases, as they were not sure it would be easily set up. They would like functional goals that would be defined and measured. Therapists were interested in a device that would give several types of feedback. Visual, audio, and tactile feedback was seen as critical features for the device. Biofeedback was seen as a desired feature by some therapists to allow therapists and their patients to have information relating to joint position, muscle use and activation. The ability for a device to detect which muscles would be active, how patients would be positioned, and presence of compensatory movements would be highly desired.
Suggestions for improvements included having end effectors with a flat support surface for the hand (rather than a half sphere) and having a longer supportive end effector to support the forearm. Motivation with interesting games was also seen as an important part to a rehabilitation robotic system.
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, and the total weight should be between 5 to 10 lbs.
Therapists' satisfaction level with current state of technology was very low, indicating there is room for RRD development. This may have been due to their lack of experience with current robotic technology given a lack of technology availability. Current robotic technology may not be used as these devices do not meet therapists' needs.
In summary, there are several changes that need to be incorporated into the next iteration of the mechanical design. The device should 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 design. There were set up challenges with making the device housed in two cases. Housing the device in one case would make setup easier, only if safety concerns can be addressed. The device should be smaller as well.

3.2. Preliminary Biomechanical Analysis

Understanding the kinematics and kinetics produced on the upper limb joints while a patient is interacting with the RRD can aid in quantitatively determining the necessary workspace and torque requirements. We measured the range of motion and amount of torque and force produced by the wrist, elbow, and shoulder joints while healthy subjects (n=4) performed transverse and sagittal reaching motions (Figures 4-5) at six different settings. These measured values were compared to reference values in the literature of joint angles and moments of subjects while performing ADLs. A full description of the biomechanical analysis process can be found in [16].
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 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 and measurements were made on healthy subjects. However, there were two sources of data which recorded the kinematics [26, 27] and one source which had kinetic data for common ADLs [26]. There were other sources of data as well, however two sources were chosen for ease of comparison. These two sources were chosen as they covered more ADLs and/or provided more data. 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 slightly different seating positions would affect the minimum and maximum angles.

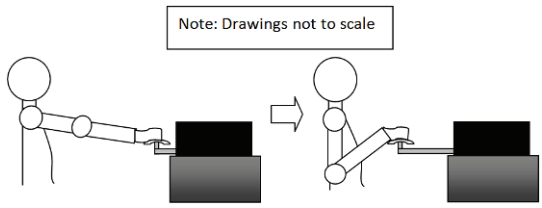

Figure 4. *Sagittal reaching motion*

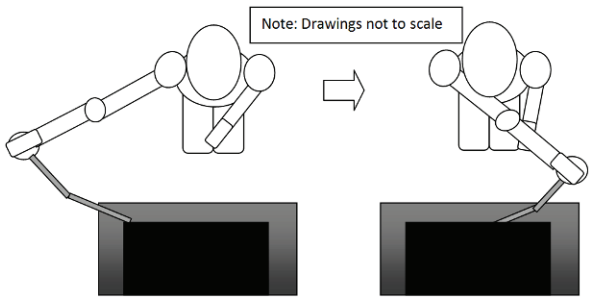

Figure 5. *Transverse reaching motion*

3.2.1. Results and Discussion

Table 3 summarizes the results of the study. For each participant, the average ROM was divided by the average ROM in the literature. For the forces and moments, the average maximum forces and moments were divided by their respective counterparts.
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. However given the wide range of values from the pilot, more biomechanical studies would need to be done for

Table 3. Summary of biomechanical evaluation. Results are as a percentage of the reference value in literature. ROM are averages and forces and moments are average maximums.

	Wrist	Elbow	Shoulder	
			Plane of elevation†	Angle of elevation
Sagittal ROM	34±10%	44±12%	121±13%*	63±13%*
Transverse ROM	147±42%*	45±15%*	157±15%**	58±6%**
Sagittal motion force (anterior)	No comparables in literature	35±30%	124±109%	
Sagittal motion force (posterior)		148±76%	110±67%	
Sagittal motion force (medial)		No comparables	139±85%	
Sagittal motion force (lateral)		38±19%	99±49%	
Sagittal motion moment (clockwise)		110±52%*	153±84%*	
Sagittal motion moment (counter-clockwise)		38±29%*	106±70%*	
Transverse motion force (anterior)		31±19%	109±69%	
Transverse motion force (posterior)		152±96%	112±67%	
Transverse motion force (medial)		No comparables	150±68%	
Transverse motion force (lateral)		24±16%	83±45%	
Transverse motion moment (clockwise)		124±64%*	121±72%*	
Transverse motion moment (counter-clockwise)		19±22%*	64±54%*	

†Reference used abduction/adduction
*values for 3 participants (data was unusable for one)
**values for 2 participants (data was unusable for two)

conclusive results.

The arms of 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. However, this may not need to be increased as the shoulder plane of elevation had more than enough movement. 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.

Comparing the force data to the reference, the forces produced on the joints were more than what Murray and Johnson [26] measured in their common ADLs. This would indicate that the forces may be decreased without compromising the ability of the device to rehabilitate arm movement used for performing ADLs. Increasing the link lengths would effectively decrease the force on the joints.

This preliminary biomechanical analysis would be a starting point to evaluate the device with stroke survivors and with therapists. As part of the user-centered design process, this type of evaluation would be critical to understanding how working with an RRD would compare to conventional therapy. Ideally a biomechanical analysis of conventional upper limb stroke therapy would be conducted to give a standard for comparison to the device use.

4. Discussion of User-Centered Design Process

This study applied principles of user-centered design to guide the development of an upper limb RRD. In some ways, the development process was successful, in other ways, challenging, but overall, the process was considered to be useful. The following are techniques that were employed in this research:

Using work practices of the user to 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. Observations of end user workflow were found to be very useful in determining general requirements for the device. These observations may not have come out through a focus group, as implicit knowledge may be difficult to articulate and self-reported behavior may be different than actual behavior.

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. While not reported here, stroke survivors are currently being recruited to participate in focus groups to evaluate this prototype iteration. The involvement of representative users was very valuable in understanding current practices and needs. Further involvement would be critical for the success of future RRDs.

The development should undergo many iterative cycles to come up with requirements from the end users. This paper describes one iteration in the user-centered design process. Future iterations should involve stroke therapists and stroke survivors, as well as stroke survivor caregivers. The design of the device, including software, and user interfaces, ideally would go through many cycles of design, feedback, evaluation, and redesign. User-centered design was used mainly for software application or systems design [14], thus going through many iterations would be simpler than with a hardware product. It would have been easier to use paper prototypes or mock ups during the initial evaluation stage of the product, allowing faster iterations at the beginning while still involving the end user. The involvement of the end user is important in determining the direction of the product early on.

Prototypes should be created early and continuously to visualize and evaluate ideas. One prototype was created to visualize and evaluate. Future iterations should continue to include prototypes for visualization and evaluation. The development of the RRD required a multi-disciplinary team. Often in working in cross disciplines, misun-

derstandings may arise as to the envisioned end product. These misunderstandings can be reduced through having physical prototypes. This was found to be true in our case as engineers and therapists often had different ideas about what certain terms meant.

The development process should be performed by interdisciplinary teams. The development process involved occupational therapists, physiotherapists, and engineers to develop the prototype. As design flaws came up, the industrial partner made 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. Therefore a closer working relationship between design, manufacturing, and end users would improve the process. It was valuable to obtain the different opinions of different experts to determine the design of the RRD.

5. Future Work

It is recommended that further cycles of iterative design and assessment be incorporated into the development of a RRD. Based on the results from Phase 3 of this research, 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. Make the device smaller 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 and non-conductive materials for the arm links and the housing
6. Construct different end effectors which can accommodate people with different degrees of upper extremity recovery
7. Develop end effectors with therapists which could secure the hand more effectively
8. Develop trunk and arm position sensors to ensure proper positioning

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 as design changes arise. It may also be useful to conduct additional therapist focus groups in different locations, for example, different countries as treatment approaches differ from country to country.

It is also recommended that a full biomechanical study on the ROM and forces that 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.

Other work related to developing a robotic system for upper limb rehabilitation is already under way. An intuitive graphical user interface (GUI) for both therapists and stroke survivors and engaging rehabilitation games are currently being developed and evaluated by therapists. Work on an artificially intelligent controller capable of adapting to the rehabilitation needs of stroke survivors is in progress [28].

6. Conclusions

This research employed user-centered design techniques to capture the requirements, build a working prototype, and conduct an evaluation of a RRD for upper limb stroke therapy. Observations of stroke therapy and a therapist survey were able to capture therapist requirements for a RRD. Using these data, a prototype RRD was designed through the House of Quality approach. The prototype was evaluated through a therapist focus group and a preliminary biomechanical analysis. While there is much future work to be done, this research represents the first stage in the development of a clinically-relevant and low cost RRD for upper limb stroke rehabilitation. Many more iterations are likely needed before a device is created that is ready for the consumer market, however, feedback from therapists regarding this first prototype were quite positive, indicating that this first iteration has produced a device that is a step in the right direction.

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