Developing Accessible Teleoperation Interfaces for Assistive Robots with Stakeholders

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Abstract

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Mobile manipulator robots have the potential to empower individuals with motor limitations to interact with the physical world around them. While many interfaces have been developed for teleoperating complex robots, most of them are not accessible to people with motor limitations or are rigid with limited configurations. Further, they are not readily available to download and use. To address these barriers, we developed the AccessTeleopKit: an open-source toolkit for creating custom and accessible robot teleoperation interfaces based on cursor-and-click input for the Stretch 3 mobile-manipulator. The toolkit was developed through several years of iteration involving three key stakeholders: (1) people with motor limitations, (2) their caregivers, and (3) occupational therapists (OT). The robot was deployed in the home of an older adult with quadriplegia and his wife/primary caregiver, with the help of an OT who helped focus the robot's functionality on enabling the end-user to achieve his goals. This dissertation presents a multi-year design and development process with stakeholders that lead to the AccessTeleopKit and recommendations on how to design robots for the OT toolbox. We lay the groundwork for enabling the deployment of assistive robots in homes with the assistance of OTs.

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DEDICATION

To the kindest and most loving German Shepard, Sparky Peddu. I hope you're chewing on an endless supply of tennis balls in doggy heaven.

Chapter 1

INTRODUCTION

The World Health Organization estimates that 190 million people globally live with some form of physical or motor limitation. These limitations, whether they are due to congenital conditions, injury-related, or acquired with age, often mean dependence on caregivers for many activities of daily living, and a reduced sense of agency and quality of life [52]. Mobile manipulator robots, such as the Stretch [47], have the potential to bridge this gap by serving as a tool for people with motor limitations to physically manipulate the world around them. While robots autonomously performing assistive tasks in unstructured homes is still a distant vision, teleoperated robots that are directly controlled by users are now within reach in terms of price, robustness, and safety. However, to serve the purpose of enabling access to the physical world, the interfaces for operating these robots need to be accessible to those users with motor impairments.

For the past three years, we have been working with Henry Evans, an end-user who is non-speaking and has quadriplegia, to develop an accessible teleoperation interface with extensive options for customization. With the help of an interdisciplinary team of researchers, we have deployed Stretch along with the teleoperation interface in Henry and Jane Evans' home. While many factors contributed to Henry's achievements with Stretch, we believe one of the key ingredients in the success of the project was the central role of an occupational therapist (OT). OTs work with clients[1] to understand their occupational goals in terms of daily self-care, productivity, and leisure [10]. They then assess the challenges their clients face in achieving those goals and implement interventions that can help address those challenges. Such interventions come from a vast array of tools in the "OT toolbox". In our collaboration, the OT was able to provide Stretch as a tool to their client, Henry, as a result of the robotics expertise available on the team.

This dissertation outlines the multi-year design and development process that lead to the AccessTeleopKit: a toolkit for creating custom and accessible robot teleoperation interfaces based on cursor-and-click input for the Stretch mobile-manipulator. We highlight the value of customization and how the customizability of the toolkit enhanced the user experience

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[1] In occupational therapy, the term "client" is commonly used to refer to the individual receiving services. We use the term "client" and "end-user" interchangeably.

for our end-users. Finally, we present recommendations for how to design assistive robots for the OT toolbox. This dissertation lays the groundwork for enabling the deployment of assistive robots in homes with the assistance of OTs.

1.1 Contributions

The goal of this thesis is to enable the deployment of assistive robots for people with motor impairments through a customizable teleoperation interface with the assistance of OTs. To that end, we have made the following contributions:

1. An evaluation of the impact of customization for teleoperation interfaces for assistive robots (Chapter 4; published in RO-MAN. [68])

2. The AccessTeleopKit: a toolkit for creating custom and accessible robot teleoperation interfaces based on cursor-and-click input for the Stretch mobile-manipulator (Chapter 5 & 7)

3. The real-world deployment and testing of Stretch in the home of an end-user (Chapter 6; published in HRI [67])

4. An analysis of barriers that stand in the way of OTs prescribing physically assistive robots and recommendations for how to design robots for the OT toolbox (Chapter 8 & 9)

Chapter 2

RELATED WORKS

2.1 Physically Assistive Robots

A growing community within robotics is working to develop robots that can assist people with physical limitations. We conducted a literature survey that provides a detailed landscape of research in physically assistive robots [59]. While some researchers aim to develop autonomous robot capabilities for assisting specific activities such, as feeding [63] or dressing [12], others have focused on general-purpose teleoperated robots that can be used for any activity (e.g., [8, 18, 30]). The survey reveals that a majority of prior work on physically assistive robots for individuals with disabilities do not involve participants with disabilities in their studies. However, recent research emphasizes the importance of involving stakeholders in various roles (e.g., not just as participants but as co-designers or community researchers) [58]. OTs have not been considered as potential stakeholders for robot development until recently (e.g., [6]). With more and more robots being evaluated outside labs in clinical or home settings, we believe that the role of OTs in getting assistive robots to end-users will become evident to roboticists.

2.2 Teleoperation Interfaces

While teleoperation is often considered less appealing by roboticists, it has several advantages in assistive scenarios. First, teleoperation is feasible and ready to deploy now, while generalizable and robust autonomy remains extremely challenging for unstructured home environments. Second, teleoperation is general-purpose; it can allow the user to perform any number of tasks as long as it is physically possible for the robot. Third, prior work has revealed that users prefer to have control of the robot in some situations, even when autonomy is possible [49, 7, 6]. Indeed, a subset of the work within assistive robotics has focused on teleoperation rather than autonomous robots [68, 8, 18, 30].

Beyond assistive robots, research on robot teleoperation has led to a large variety of interfaces across different types of robots and application areas [14] including operation of robots in hostile environments for humans such as disaster areas [56, 72] or space [24], as well as a way to enhance human manipulation for surgery [53]. A recent surge in new teleoperation interfaces has been driven by motivation to collect demonstrations for training autonomous capabilities (e.g., [70]). For most of this work, accessibility and customizability have not been a priority given their application domain or specific purpose. Nevertheless, a long line of research in the human-computer interaction community on accessibility and customization of GUIs (e.g., [37, 11, 26]) is applicable to robot teleoperation interfaces and has informed our work.

2.2.1 Input Modalities for Teleoperation Interfaces[1]

There are several input modalities that have been proposed for teleoperation interfaces. Some works use **direct processing**, such as electromyography (EMG) or electroencephalogram (EEG), to convert the user's neural signals into inputs to the robot. Most works used EMG or EEG to teleoperate a robot in the pick-and-place domain of assistance [75, 25]. Others combined EMG/EEG with another input device, such as muscle contraction [51, 3], brain signals [64] or eye gaze [78], to teleoperate the robot.

A larger set of papers involve indirect processing through modalities of audition, touch, and kinesthetic inputs. The **audition** modality contains sensors that *hear* user inputs and send them to the robot. This includes interfaces that allow the user to give vocal commands to teleoperate a robot arm [36, 66]. While audition sensors have the benefit of not requiring any body motion on the part of users, they may not work well in noisy settings [31] or social settings [57, 7]. The **touch** modality contains sensors that *feel* user inputs through direct contact and send them to the robot. This includes traditional methods of interacting with technologies, such as a mouse and keyboard [9, 8], joystick [66, 76, 50]. The **kinesthetic** modality contains sensors that *feel user motion* and send them to the robot. This includes using inertial measurement units (IMUs) to sense users' head [39, 51, 3, 62, 61] and upper body movements [42, 13] for teleoperation, or using rotary sensors [45] or pressure sensors [17] for teleoperation.

While these works explore a wide variety of input modalities for teleoperation interfaces, they are not necessarily accessible to users with diverse motor impairments. For example, the audition modality is not accessible to someone who is non-speaking, the kinesthetic modality that involves upper body movements is not accessible to someone paralyzed from the neck down. Additionally, some of these works require additional devices, however, past research has demonstrated that users want to limit the number of additional devices they have to work with in order to use an assistive technology [57]. In this dissertation, we specifically explore using a web-based teleoperation interface as it is compatible with a wide variety of

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[1] This section was adapted from our prior publication [59]

existing assistive input devices used by individuals with a wide range of motor impairments.

2.3 Customization and Accessibility

While customization has been widely explored in the human-computer interaction community [37, 11, 26], it has not been explored for robot teleoperation interfaces. Instead, much of the work on customization in robotics has focused on the levels of assistance the robot provides [40, 44, 21, 22, 32, 48, 28, 33, 1] or the level of autonomy the robot has [7, 46, 41, 79, 69].

However, these teleoperation interfaces provide a single control configuration that may not be accessible to users with different abilities or necessarily satisfy users' preferences. Making control interfaces customizable will make them accessible to users with unique physical abilities and fit user preferences. Ability-based design advocates for interface adaptation–the user should not have to conform to the system, rather the system must adapt to the user [80]. A participant, with motor impairments, in a user study from prior work specifically emphasized the need for flexible interfaces that cater to people with motor impairments [8]. Furthermore, prior work has shown that allowing people to customize teleoperation interfaces impacts their task completion time and subjective preferences [9].

2.4 Occupational Therapists and Assistive Technology

The importance of the OT's role in the design and implementation of assistive technology has been acknowledged in prior accessibility and human-computer interaction research. For instance, Hoffman et al. observed the use of fabrication technology by OTs and co-designed software solutions to better support use of fabrication in occupational therapy [35]. Su et al. interviewed occupational therapists to understand how they assess accessibility of physical spaces to develop AI-based tools that can assist with this assessment and recommend modifications that improve accessibility [73]. One formative study by Bhattacharjee et al. involved a questionnaire for OTs with expertise in feeding assistance to inform the design of assistive feeding robots [6].

In our work, we deployed Stretch in an older adult couples' home. This deployment was facilitated by an OT whose role was as follows:

1. **Occupational Profile.** The OT developed an occupational profile of their clients, the older adult couple (Fig. 3.1). The occupational profile is a summary of a case participant's history and experience, activities of daily living, interests, values, needs, and relevant contexts.

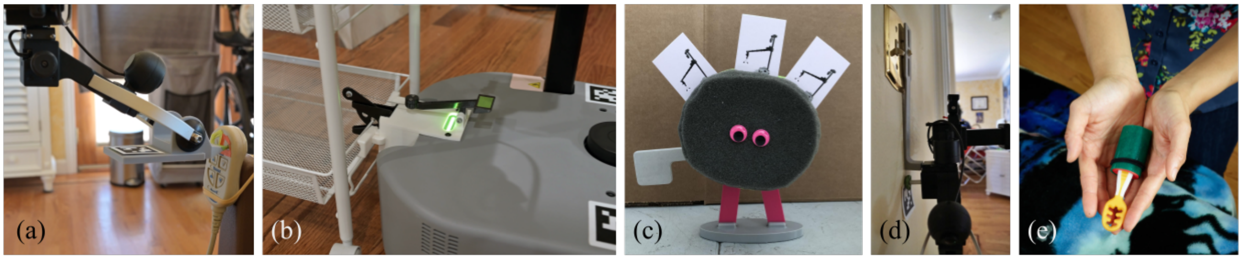


Figure 2.1: Tools and physical environment modifications developed by the OT to enable the lead user in our formative study to perform his desired tasks with Stretch: (a) button pusher for adjusting bed height, (b) hitch connector for towing carts, (c) a cardholder for card games, (d) a light-switch adapter, (e) an adapted feeding tool. Additional examples are shown in Fig. 4.2.

2. **Intervention Planning.** The OT then developed strategies and activities to address the specific needs and goals identified in a client's occupational profile.
3. **Physical environment adaptation.** The OT collaborated with engineers to create tools that the lead user could use with Stretch to complete a variety of tasks. Some tools developed included a button pusher, a hitch that attaches to carts for towing, and a cardholder so that the lead user can partake in card games more independently (Fig. 2.1).

Throughout the project, the OT played a crucial role in understanding the clients' needs and goals, as well as in developing tailored interventions that take advantage of the robot's capabilities to address these goals. By leveraging the OT's expertise, we were able to optimize the functionality and usability of the Stretch robot, ultimately enhancing the quality of life for the user.

2.4.1 Barriers for Prescribing Assistive Technology

Thawisuk et al. conducted an in-depth literature review on OTs perspectives for prescribing ATs for older adults [74] and identified several barriers. Some of these barriers include:

1. **Heavy Workload**: OTs may face a heavy workload, which can lead to difficulties in providing adequate follow-up care and prioritizing clients in need of AT services [65].

2. **Lack of Research**: There may be a lack of research to support clinical decision-making during the prescription of AT, which can lead to difficulties in identifying and

providing appropriate assistive devices for clients [71].

3. **Affordability, ease-of-use and motivation**: Clients' affordability of the device, ease of device use [55, 19], and client and caregiver motivation to use the prescribed assistive device [65] can be barriers to prescribing AT.

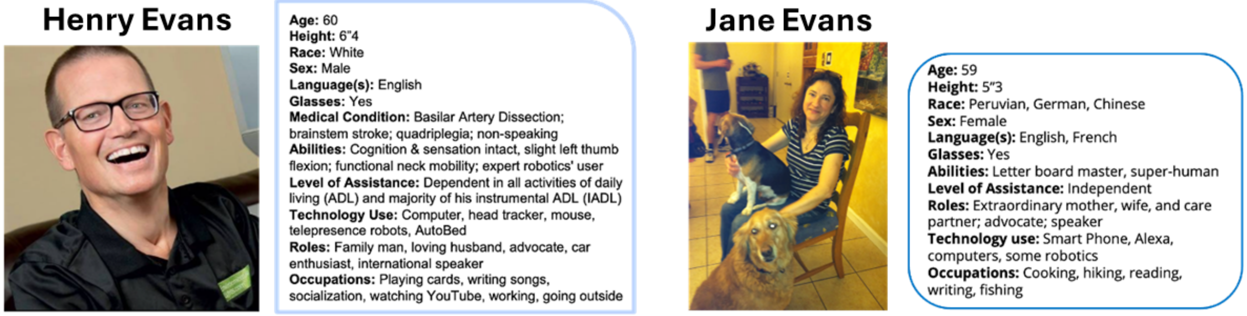
Existing studies have also found that OTs have difficulty accessing information about what assistive technology is available, making it a barrier to prescribing these alternative solutions [43, 77, 5, 55]. We aim to understand how these barriers and any additional barriers might affect the prescription of assistive robots to clients with motor impairments.

2.4.2 Adapting Assistive Technology

Abandonment is a long-standing issue with off-the-shelf AT because it may not adequately meet the users' needs [27, 38]. To address this issue, OTs often adapt existing off-the-shelf AT to better suit their clients' needs [20, 34, 35]. In a study conducted by Aflatoony et al. [2], OTs stated that this need arises because of distinctive aspects related to an individual client's specific physical or cognitive capabilities, the context of usage, or limitations inherent in the product itself.

Chapter 3

DEVELOPMENT OF AN ACCESSIBLE ASSISTIVE ROBOT WITH STAKEHOLDERS



Henry Evans

Age: 60
Height: 6"4
Race: White
Sex: Male
Language(s): English
Glasses: Yes
Medical Condition: Basilar Artery Dissection; brainstem stroke; quadriplegia; non-speaking
Abilities: Cognition & sensation intact, slight left thumb flexion; functional neck mobility; expert robotics' user
Level of Assistance: Dependent in all activities of daily living (ADL) and majority of his instrumental ADL (IADL)
Technology Use: Computer, head tracker, mouse, telepresence robots, AutoBed
Roles: Family man, loving husband, advocate, car enthusiast, international speaker
Occupations: Playing cards, writing songs, socialization, watching YouTube, working, going outside

Jane Evans

Age: 59
Height: 5"3
Race: Peruvian, German, Chinese
Sex: Female
Language(s): English, French
Glasses: Yes
Abilities: Letter board master, super-human
Level of Assistance: Independent
Roles: Extraordinary mother, wife, and care partner; advocate; speaker
Technology use: Smart Phone, Alexa, computers, some robotics
Occupations: Cooking, hiking, reading, writing, fishing

Figure 3.1: A summary of the occupational profiles developed by the OT that facilitated the home deployment.

3.1 Stakeholders

In this dissertation we collaborated with three stakeholders: (1) the end-user, Henry Evans (2) the end-user's wife and primary caregiver, Jane Evans, and (3) an OT, Vy Nguyen.

3.1.1 End-User: Henry Evans

We have tested various iterations of the AccessTeleopKit during user studies. However, we have worked closely with one user who has been critical to the design and development of the AccessTeleopKit: Henry Evans. In 2002, Henry Evans had a stroke-like attack, and overnight, he became a non-speaking person with quadriplegia. He has paralysis from the neck down and can only move his head and his left thumb. He uses a head tracker to move the cursor on his computer and clicks with a mouse that is taped to his hand. His primary mode of communication is through a letter board. Henry is a loving husband, a caring father and grandfather, and a playful individual. These qualities show through the tasks and activities he has chosen to do with Stretch: surprising his wife with a rose, playing games with his granddaughter, and card games with friends and family.

3.1.2 Caregiver: Jane Evans

Jane Evans is Henry' wife and primary caregiver, a loving mother, grandmother and friend. She is fully independent and is a master at using the letter board; she can even visualize the letters and communicate with Henry without a physical board. Jane is often on the receiving end of interactions with Henry through Stretch and has contributed to the design of those interactions as well as the design for a mobile interface that she can use to teleoperate Stretch.

3.1.3 Occupational Therapist: Vy Nguyen

Dr. Vy Nguyen is a licensed OT who has facilitated three home deployments with Stretch. She is skilled in making home modifications to increase accessibility for both the robot and user, as well as making custom tools that Henry was able to use with Stretch to complete his desired occupations. Vy's goal is to enable users' to achieve their desired occupations with Stretch while including the caregiver in the process.

3.2 Development Timeline

The AccessTeleopKit was developed based on findings through several years of iteration of the teleoperation interface with end users. The development timeline is outlined in Fig. 3.2.

3.2.1 Initial Development & Evaluation

The original interface was developed by Dr. Charlie Kemp. This version of the interface included two fish-eye video streams with buttons overlaid on the video streams that provided discrete control of the joints. Cabrera et al. [8] built additional features for the interface, such as controls for adjusting the speed, however, used only used the realsense D435i camera view. They confirmed the utility of such a robot in the homes of people with motor impairments. However, several challenges were noted by participants:

C1 The interface only offered discrete controls, and participants found the repetitive clicking fatiguing. Participants requested continuous controls to alleviate the fatigue.

C2 The camera view was obstructed by the robot's arm when the height of the object being manipulated was close to camera position.

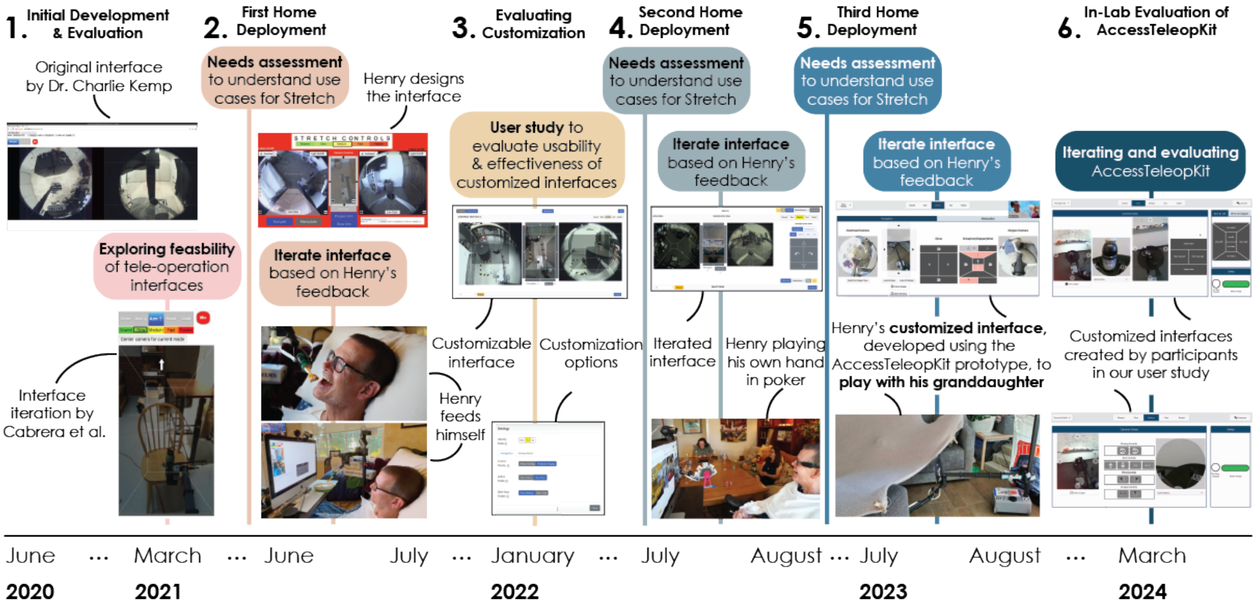


Figure 3.2: Timeline of the development of AccessTeleopKit.

- **C3** Participants struggled with depth perception.
- **C4** Participants found frequent mode switching between base and arm controls to be challenging.
- **C5** Participants lacked awareness of the physical embodiment which would result in collisions. For example, participants would forget to retract the robot's arm before driving.

3.2.2 First Home Deployment

Stretch was embedded in the home of Henry and Jane Evans with the assistance of an OT. Henry used Stretch to complete a variety of tasks including feeding, scratching itches, and playing card games. This deployment began with a needs assessment to identify tasks that were valuable for Henry and feasible to do with Stretch. The deployment consisted of two 2-week sessions in the couple's home. Any iterations made to the interface were done by the research team remotely, and the software was then manually updated by the occupational therapist on-site. During this deployment, the Henry tested the interface created by Dr. Charlie Kemp and Cabrera et al. [8]. He created a design for the interface that combined elements of both interfaces. His design addressed **C2** by incorporating additional cameras views that would not be occluded by the robot. The design was implemented after the deployment.

3.2.3 Evaluating Customization

Following the deployment, we explored customization of the interface [68]. Prior to this work, there was a fixed interface that was co-designed by Henry from the home deployment. This work was motivated by the need for creating interfaces that can cater to the needs and preferences of all users. This was explicitly expressed by a participant in a prior study [8]. Furthermore, Ability-based design advocates for interface adaptation–the user should not have to conform to the system, rather the system must adapt to the user [80]. We built on Henry's design to include continuous control options to address **C1**. Additionally, they included a subset of base controls in the *Manipulation* mode to reduce mode switching (**C4**). This work confirmed the utility of such a robot and the value of customization. Depth perception (**C3**) and lack of awareness of physical embodiment (**C5**) continued to be a challenge. Participants also faced additional challenges:

- **C6** Participants wanted to change their settings during the task, as their preferences in settings varied depending on the context of the task.
- **C7** Participants wanted to change the layout (e.g. hide camera views, move controls, etc.)

3.2.4 Second Home Deployment

Stretch was embedded in Henry and Jane's home for a second summer with the interface we developed in prior work [68]. This deployment was led by an OT and engineer. The deployment consisted of two 2-week sessions in the couple's home. New tasks performed by Henry via the Stretch included operating his percussion vest and flipping a light switch. Any iterations made to the interface were made on-site by the engineer and between the sessions. Similar to participants in the prior study, Henry had a different preference in layout (**C7**). He requested the controls overlaid on the camera views to be separated out into its own button pad, as he found the overlaid control distracting.

3.2.5 Third Home Deployment

We embedded Stretch in Henry and Jane Evans' home for a third summer using the prototype of the AccessTeleopKit. The prototype addressed all challenges except lack of awareness of physical embodiment (**C5**). The deployment consisted of three 1-week sessions in the couple's home. Henry created different interfaces for different tasks. Any iterations made to the interface were made on-site by the engineer and between the sessions. Henry's feedback was incorporated into the next iteration of the AccessTeleopKit.

As part of this exploration, Henry expanded on the types of task he carried out using the robot, including moving wheeled carts and other items around the house and playing with his granddaughter. He has been unable to play and have a relationship with his three-year-old granddaughter due to his disability, and wanted to use the robot to play with her. Jane has shared that, *"Our granddaughter looks at [her grandfather] as an inanimate object, and there's a sadness in that. [Henry] has shared with me how sad it is"*. Henry was able to play with his granddaughter for the first time via Stretch and the AccessTeleopKit. This has greatly improved his relationship with her.

3.2.6 Evaluation of the AccessTeleopKit

We iterated on the prototype to address feedback from the Henry during the third summer deployment, as well as evaluate the interface with multiple people with motor impairments that are representative of our target population.

Chapter 4

IN-LAB EVALUATION OF CUSTOMIZATION OF REMOTE TELEOPERATION INTERFACES FOR ASSISTIVE ROBOTS

In this chapter, we describe our evaluation of customization of remote teleoperation interfaces for operating a Stretch RE1. More specifically, we build on prior work done by Cabrera et al. [8] by adding additional control features and analyzing user preferences and performance when using different interface configurations. We ran two studies with users without motor impairments, who could serve as a caregiver, (N=13) and users with motor impairments (N=10). In these studies, users learn how to use the various control settings in the interface and are asked to complete a series of tasks using default settings determined by prior work and their own customized settings. We have three hypotheses:

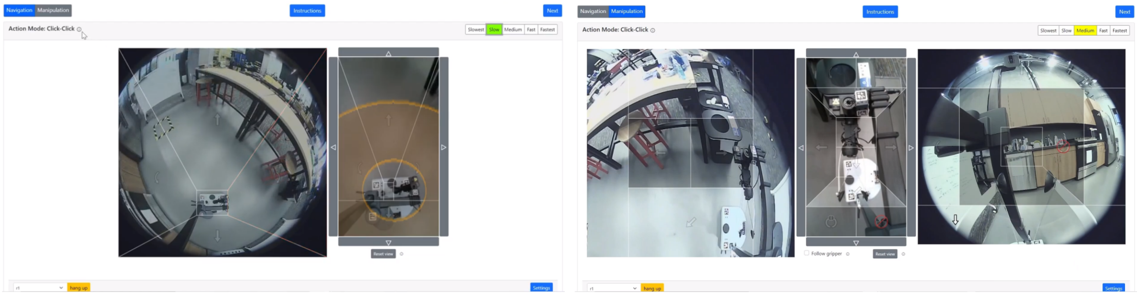
H1 No single interface configuration will satisfy all users' needs and preferences.
H2 Users with motor impairments will have different preferences than people without.
H3 Users' task completion time, number of errors and clicks will be lower when using their customized settings.

4.1 Robot System: Stretch RE1

The Stretch RE1 mobile manipulator is developed by Hello Robot [47]. Stretch has a telescoping arm that extends 50cm horizontally and is attached to a prismatic lift that reaches 110cm vertically. The arm has a 1 degree of freedom gripper attached to a rotational joint. The movement of the arm is orthogonal to the movement of the differential drive base. Stretch has a Realsense camera attached to a pan-tilt head and two fixed fish-eye cameras: one with an overhead view of the base and arm and the other with a view of the gripper. Stretch's lightweight (24.5kg) and safe design, and physical capabilities make it feasible for long term deployment in end-users' homes. Stretch has open source software in python, ROS1, and ROS2.

4.2 Remote Teleoperation Interface Design

The remote teleoperation interface for Stretch has two distinct modes that can be toggled by switching tabs in the top left corner of the interface. Each mode has controls for controlling



Action Mode: Click-Click

(a) Navigation mode

(b) Manipulation mode

Figure 4.1: Overview of the modes in the teleoperation interface.

a different subset of the robot's actuators. The **Navigation** mode (Fig. 4.1.a) controls the mobile base and the **Manipulation** mode (Fig. 4.1.b) controls the arm height, extension, and gripper. The **Navigation** mode has two camera views: (1) a fixed overhead fish-eye camera view and (2) an overhead camera view with pan/tilt controls. The **Manipulation** mode has the same two camera views, as well as a fish-eye camera view from the gripper's perspective. Each mode has its own subset of *control displays* and *action modes* that can be selected in the settings menu.

4.2.1 Action Overlay Control Display:

This control display has buttons overlaid on each camera view that control different actuators on the robot. The **Navigation** mode has two translation and two rotation actions. The **Manipulation** mode has two buttons to control each of the following degrees of freedom: the arm's height, the arm's extension, gripper rotation in/out, open/close the gripper, and translation for the mobile base (for a total of 10 buttons). When the cursor hovers over a button, an icon overlaid indicates the action and a tooltip text appears with explanation. In the **Manipulation** mode, the icon turns red when a joint is in collision with an object, and a red stop sign appears over the icon when a joint has reached its limit. The user can control the speed of the robot by selecting from five preset speeds. The button outline turns red while the robot executes the corresponding action.

4.2.2 Predictive Control Display:

This control display overlays a trajectory on the fixed overhead fish-eye view of the robot's base and is only applicable in the **Navigation** mode. The length and curve of the trajectory

(a) Task 1 (b) Task 2 (c) Task 3

Figure 4.2: Overview of all tasks: (a) Navigate to the fridge, (b) pick up cube on the table, and (c) Toss the trash on the stove in the recycling bin

affect the speed and heading of the robot, respectively. The longer the trajectory, the faster the robot will move, and the shorter the trajectory, the slower the robot will move. If the user presses anywhere behind the base, the robot will move at a fixed speed backwards. If the user presses on the left side of the base, the robot will rotate to the left and will rotate to the right if the user presses on the right side of the base. The trajectory turns red when the robot is moving.

4.2.3 Action Modes

All action modes are applicable to both control displays. In the **Step Actions** mode, the robot moves for two seconds when the user presses the button or trajectory. The distance the robot moves is determined by the speed. In the **Press-Release** mode, the robot moves when the user presses and holds the button or trajectory and stops when they release. Finally, in the **Click-Click** mode, the robot moves when the user clicks the button or trajectory and stops when they click again.

4.3 Study Design

4.3.1 Environment & Tasks

The study was conducted in a kitchen setting with a working area of roughly 2.15x4 meters. The tasks involve driving the robot to a specific position and orientation, picking up a cube, and recycling trash. Tasks involve a combination of observing the environment, navigating, manipulation and collision avoidance:

T1 The user drives the robot from a starting position into a square in front of the fridge. They must orient the robot to face the fridge (Fig. 4.2a)

T2 The user must control the robot to pick a cube up off a table. The robot is positioned next to the table (Fig. 4.2b)

T3 The user must drive the robot from the fridge to the stove, pick up a piece of trash on the stove, drive to the recycling bin and drop the trash in the bin (Fig. 4.2c)

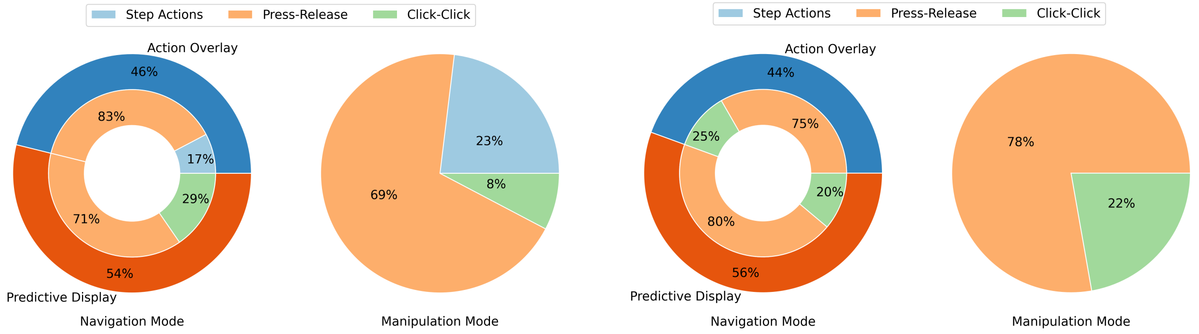
4.3.2 Procedure

Participants join a video conferencing call through Zoom with screen sharing capabilities. They then log into the web interface for controlling the robot. Participants were located all around the U.S. and were not physically present. The user begins by watching an overview video of how the robot and interface works. In the first phase of the study, the user explores how to use the action overlay control display in the navigation mode. They watch video tutorials on how to use each of the action modes. After each video, they have a chance to become comfortable with the controls. They then complete Task 1 with the default settings and customized settings. They customize their settings by selecting their preferred action mode in the settings menu. The default setting is the step actions mode, which was the original action mode provided by the interface developed by Dr. Charlie Kemp.

In the next phase of the study, the user explores that predictive display mode inspired by the Beam telepresence robot interface. Similar to the first phase, the user watches a video tutorial on how to use each of the action modes in this control display. After each video, they have a chance to become comfortable with the controls. They then complete Task 1 with the default and customized settings. The default setting is the press-release mode. This is the original action mode provided by the Beam's interface. Task 1 is considered a success when the user successfully drives the robot to the goal region and has it face the fridge.

Next, the user explores the manipulation mode. They watch video tutorials on how to use each action mode and have a chance to become comfortable with the controls. They then complete Task 2 with the default and customized settings. The default setting is the step actions mode. Task 2 is considered a success when the robot picks the cube up off the table.

In the last phase of the study, the user completes Task 3 using both the default and customized settings for both the navigation and manipulation mode. Task 3 is considered a success when the trash is dropped in the recycling bin. The default settings for the action



(a)

(b)

Figure 4.3: (a) Preferences of users *without* motor impairments and (b) users *with* motor impairments for Task 3

overlay and predictive display control displays are step actions and press-release, respectively. The default setting for the manipulation mode is step actions. After selecting their preferred settings, the user fills out a questionnaire on the customization process. Additionally, the user fills out a questionnaire after completing the task with the default settings and then again with the customized settings. After completing the task twice, the user fills out a series of questionnaire about their experience, provides suggestions and recommendations and demographic information. Note, we counterbalance the order in which the task is completed with default and customized settings.

4.4 Study with Users Without Motor Impairments

Our study was completed by 13 individuals from the general population (6 Male, 6 Female, 1 Other) with ages ranging from 20-55 (M=26, SD=9). We asked participants to rate their proficiency with technology on a 7-point Likert scale. The average rating was 5.31 with a standard deviation of 1.97. The study took 90 minutes and participants were compensated with a $50 Amazon gift card. We present our findings summarizing user setting preferences, task performance (success and efficiency), and then describe the teleoperation interface usage.

4.4.1 Setting Preferences

The preferred settings by participants for Task 3 are shown in Fig. 4.3a. In the navigation mode, 46% of participants chose the action overlay control display and 54% of participants chose the predictive display control display. Participants who chose predictive display liked the simplicity in comparison to the action overlay mode: *"Obviously, the predictive display is very nice, because it gets rid of buttons" (M, 25).* We asked participants to rate their proficiency with technology on a 7-point Likert scale. On average, participants who chose action overlay rated themselves lower (M=3.83, SD=1.86) than participants who chose predictive display (M=6.57, SD=0.49).

Overall, the press-release action mode was largely preferred in both the navigation and manipulation mode: *"I like [press-release] mode better. In the [step-actions] mode it was to touch, stop, touch, stop"* (M, 29). However, there is no subset of settings that is a clear "winner" as there is a spread across preferred control display and action mode. Note that 7.69% of participants, across the different modes, chose their customized setting to be the same as the default settings.

4.4.2 Task Success

All participants successfully completed Task 1 and 2 with both default and customized settings. All participants successfully completed Task 3 with the default settings, and 11 participants successfully completed Task 3 with the customized settings.

Despite the high success rate, we observed errors during Task 2 and 3 (Table 4.1). The average number of errors for Task 2 was higher when participants used their customized settings. We noticed most errors occurred when users selected either press-release or click-click as their preferred mode. For Task 3 the average number of errors was lower when users used their customized settings. We did not see a correlation between proficiency with technology and number of errors.

4.4.3 Task Performance

We show the time taken and number of clicks across participants when using customized and default settings for all tasks in Fig. 4.5. Note, we only plot points for users that chose settings different from the default settings. We conducted a t-test, however, due to the small sample size we, have not reached the statistical power to perform meaningful significance testing.

- Task 1 - Action Overlay: 11/13 participants had fewer clicks and faster task completion time when using their customized settings.
- Task 1 - Predictive Display: 4/5 participants had fewer clicks and 5/5 participants had faster task completion time when using their customized settings.

Task	Impairment	Setting Type	Avg	SD	Min	Max
1	Yes	Default	0	0	0	0
1	Yes	Custom	0	0	0	0
2	Yes	Default	0.5	0.92	0	3
2	Yes	Custom	0.2	0.4	0	2
3	Yes	Default	0	0	0	0
3	Yes	Custom	0.3	0.64	0	2
1	No	Default	0	0	0	0
1	No	Custom	0	0	0	0
2	No	Default	0.46	0.88	0	3
2	No	Custom	1	1.68	0	5
3	No	Default	0.46	0.88	0	3
3	No	Custom	0.31	0.48	0	1

Table 4.1: Number of errors across each task for participants with and without motor impairments

- Task 2: 9/12 participants had faster task completion time when using the default settings (step actions) irrespective of ordering. There is no clear trend for the number of clicks.
- Task 3 - Manipulation: 5/10 participants spent less time in the manipulation mode when completing the task a second time, irrespective of ordering. 6/10 participants had fewer clicks when they completed the task with their customized settings.
- Task 3 - Navigation: 6/7 participants completed the task faster when using their customized settings, but 7/7 participants had fewer clicks their second time completing the task irrespective of ordering.

Overall, participants had faster task completion time when using customized settings for navigation but had faster task completion time when doing the tasks a second time for the manipulation mode regardless of whether they used custom or default settings first. The manipulation mode is more difficult to use than the navigation mode, as there are more buttons and degrees-of-freedom to control. One participant even found the manipulation mode to be overwhelming: *"Having so many buttons makes me nervous"*. This possibly resulted in a learning curve for the manipulation mode.

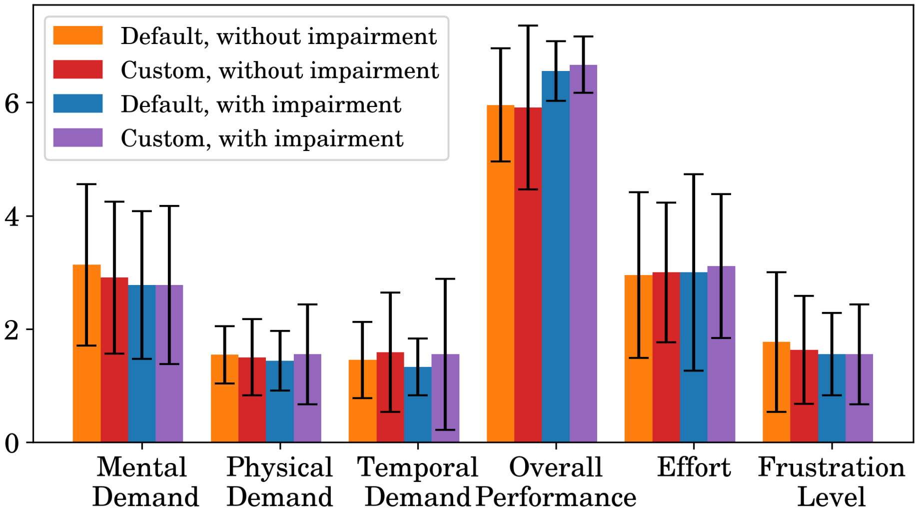


Figure 4.4: Task 3 workload for users with and without motor impairments.

4.4.4 Task Workload and Subject Evaluation

The task load index was assessed after the completion of Task 3 with both customized and default settings, and the averages are shown in Fig. 4.4. On average, the mental demand, physical demand and frustration level ratings were slightly higher with the customized settings. Interface intuitiveness, learnability, efficiency, error recovery, accessibility to participants, and satisfaction with interface settings rated similarly between the default and customized settings (Fig. 4.6).

4.4.5 Utility of Robot

All participants found the robot to be useful. Some said that the robot would not be useful in their own lives but could be useful to someone with motor impairments. Other participants said that the robot could be useful to complete tasks when they are not physically present or in hard-to-reach places such as overhead cabinets or shelves. One participant said the robot would be useful if they were sick and unable to get out of bed. They would use the robot to fetch things for them in this situation.

ID	Age	Source of Motor Impairment	Motor Impairments	Input Device
P1	46	C4 SCI	Paralysis in arms and legs	Head array
P2	21	C5/6 SCI	Paralyzed from the chest down; no tricep or finger function	Trackpad and trackball mouse
P3	33	CMT Type 2A	Paralyzed from the waist down; limited mobility in arms and hands	Standard computer mouse
P4	30	C3 SCI	Paralysis in the arms, trunk and legs	GlassOuse
P5	27	C5/6 SCI	Paralyzed from the chest down; no tricep or finger function	Trackball mouse
P6	31	Transverse Myelitis	Paralyzed from the neck down; little hand movement	Drawing tablet with stylus operated with mouth
P7	22	C5 SCI	Paralyzed from the chest down; no tricep or finger function	Trackpad
P8	33	C4/5 SCI	Paralyzed from the chest down; no tricep or finger function	Trackpad
P9	21	C5/6 SCI	Paralyzed from the chest down; no tricep or finger function	Stylus
P10	27	C4 SCI	Paralysis in arms and legs; has wrist mobility but not finger function	QuadJoy

Table 4.2: Demographic information of participants with motor impairments

4.5 Study with Users With Motor Impairments

Next, our study was completed by people with motor impairments, who are our representative target population. The study setup and procedure are identical to the first study. We had 10 participants (4 Male, 6 Female) with varying levels of motor limitations (Table 4.2) and ages ranging from 21-46 (M=30, SD=7.5). We asked participants to rate their proficiency with technology on a 7-point Likert scale. The average rating was 6 with a standard deviation of 0.87. The study took 90 minutes and participants were compensated with a $100 Amazon gift card.

4.5.1 Setting Preferences

The preferred settings by participants for Task 3 are shown in Fig. 4.3b. In the navigation mode, 44% of participants chose the action overlay control display and 56% chose the predictive display control display. Majority of participants preferred the press-release mode over other action modes for both the action overlay and predictive display control display: *"The [press-release mode] is way easier than the [step actions mode]"* **(P3)**. Participants also noted that they liked the ability to take small steps within the press-release mode (as in the step actions mode), hence allowing for both continuous and step-wise control: *"I like the [press-release mode] because you could just click, click, click for step-wise movement"* **(P8)**. None of the participants preferred the step-actions mode because of the fatigue caused by repetitive clicking.

Similar to the preferences of people without motor impairments, the press-release action mode was largely preferred in both the navigation and manipulation mode. Again, there is no subset of settings that is a clear "winner" as there is a spread across preferred control display and action mode.

4.5.2 Task Success

All participants successfully completed all three tasks. We observed errors in Task 2 with the default and customized settings and Task 3 with the customized settings (Fig. 4.1). With the default settings in Task 2 (i.e., step actions), we noticed that some participants had difficulty estimating how far the arm would move based on their speed setting. This caused the robot to overshoot when reaching for the cube and collide with the table. One participant missed grabbing the cube twice in Task 2 with the customized settings, and two participants missed grabbing the trash in Task 3 with the customized settings as they had trouble with depth perception. Overall, the number of errors was low, and participants recovered from errors and eventually succeeded in completing the tasks.

4.5.3 Task Performance

We show the time taken and the number of clicks across participants when using customized and default settings for Task 3 in Fig. 4.5. Note, we only plot points for users that chose settings different from the default settings. We conducted a t-test, however, due to the small sample size, we have not reached the statistical power to perform meaningful significance testing. **P1** is not included in this plot, as they were not able to complete the task with the default settings for the predictive display control display (press-release). Their head array was not capable of doing the press and hold cursor action.

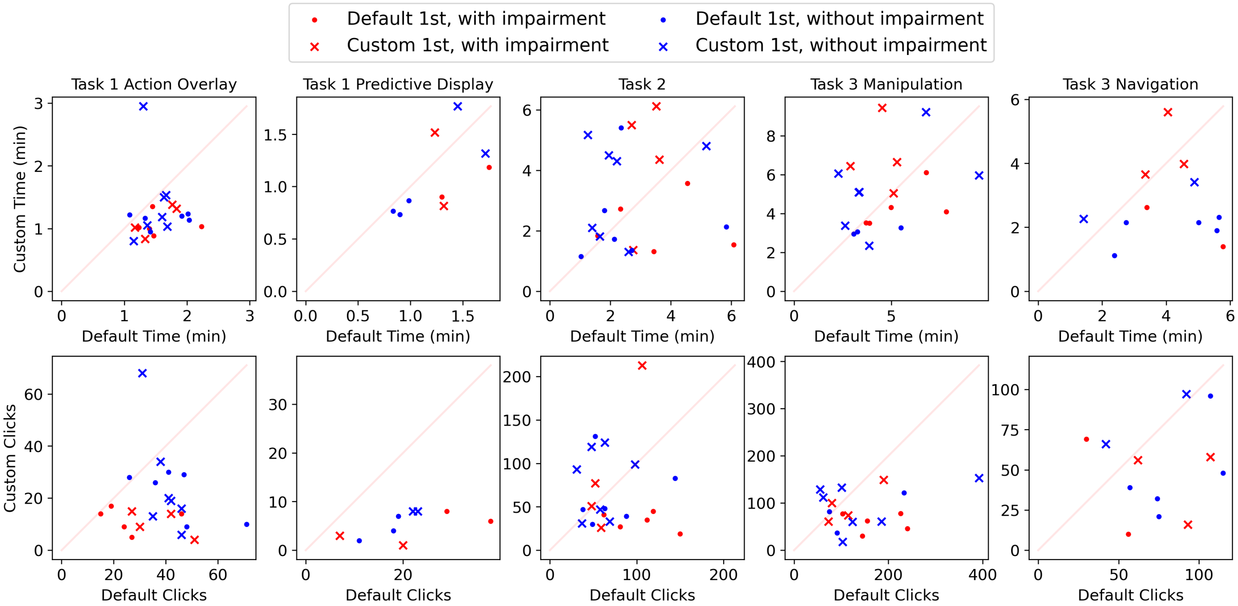


Figure 4.5: (Top) The time taken and (Bottom) number of clicks when using default versus customized settings. Participants had fewer clicks or completed the task faster with the customized settings for points under the line or default settings for points above the line. We only plot points for users that chose settings different than the default settings.

- Task 1 - Action Overlay: 9/9 participants had faster task completion time and fewer clicks when using their customized settings.
- Task 1 - Predictive Display: 3/4 participants completed the tasks faster when using their customized settings and 4/4 participants had fewer clicks when using their customized settings irrespective of ordering.
- Task 2: 6/8 participants had faster task completion time and 7/9 participants had fewer clicks when completing the task a second time, irrespective of interface settings.
- Task 3 - Manipulation: 8/9 participants completed the task faster the second time irrespective of ordering, but 8/9 participants had fewer clicks when using the customized settings.
- Task 3 - Navigation: 3/5 participants had faster task completion time and 4/5 participants had fewer clicks when using the customized settings.

Overall, participants had faster task completion time when using customized settings for navigation but had faster task completion time when doing the tasks a second time for the manipulation mode irrespective of ordering. This is possibly a result of the manipulation mode being more difficult to learn for the aforementioned reasons. P8 referred to this learning curve: *"It's really fun. I think it's more a matter of you keep doing it and getting used to it. You're just figuring it out. It's like when you get a new phone, and you don't know where things are."* **(P8)**.

4.5.4 Task Workload and Subjective Interface Evaluation

The task load index was assessed after the completion of Task 3 with both customized and default settings. The averages are shown in Fig. 4.4. Overall, all TLX ratings were very similar between default and customized settings. Interface intuitiveness, learnability, efficiency, error recovery, accessibility to participants, and satisfaction with interface settings rated similarly between the default and customized settings (Fig. 4.4). Additionally, the ratings for all categories are higher than the ratings by the participants without motor impairments. The difference in ratings between users with and without motor impairments is possibly due to the direct impact this platform could have on the users' lives.

4.5.5 Utility of Robot

All participants said that the robot is useful and that their homes could accommodate the robot. All participants said that they would use the robot to retrieve items around the household such as water (P6, P9), cooking utensils (P7), food (P7) and medical supplies (P5). Participants also said they would use it for tasks such as scratching their forehead (P6), unloading laundry (P3), putting groceries away (P10), and organization (P10). Participants with arm function and no leg function said that they would specifically use the robot to fetch them items that are beyond their reach and if they were in their bed instead of their wheelchair: *"The last place I was staying at I literally, did not get out of bed for like a month, and this would have been nice to get my water out of my fridge."* **(P9)**. Participants with no arm or leg function said they would use it more frequently so that they would not need to ask anyone for help. Most participants did not find utility for the robot outside their home, but P3, P8 and P10 said that they could use the robot when grocery shopping.

We asked participants to rate their independence on a 7-point Likert scale (M=2.6, SD=1.02). We then asked participants to state their agreement with the statement "Having the robot in my home will make me more independent" on a 7-point Likert scale (M=5.8, SD=1.6). Overall, participants believe the robot is useful and will enhance their independence.

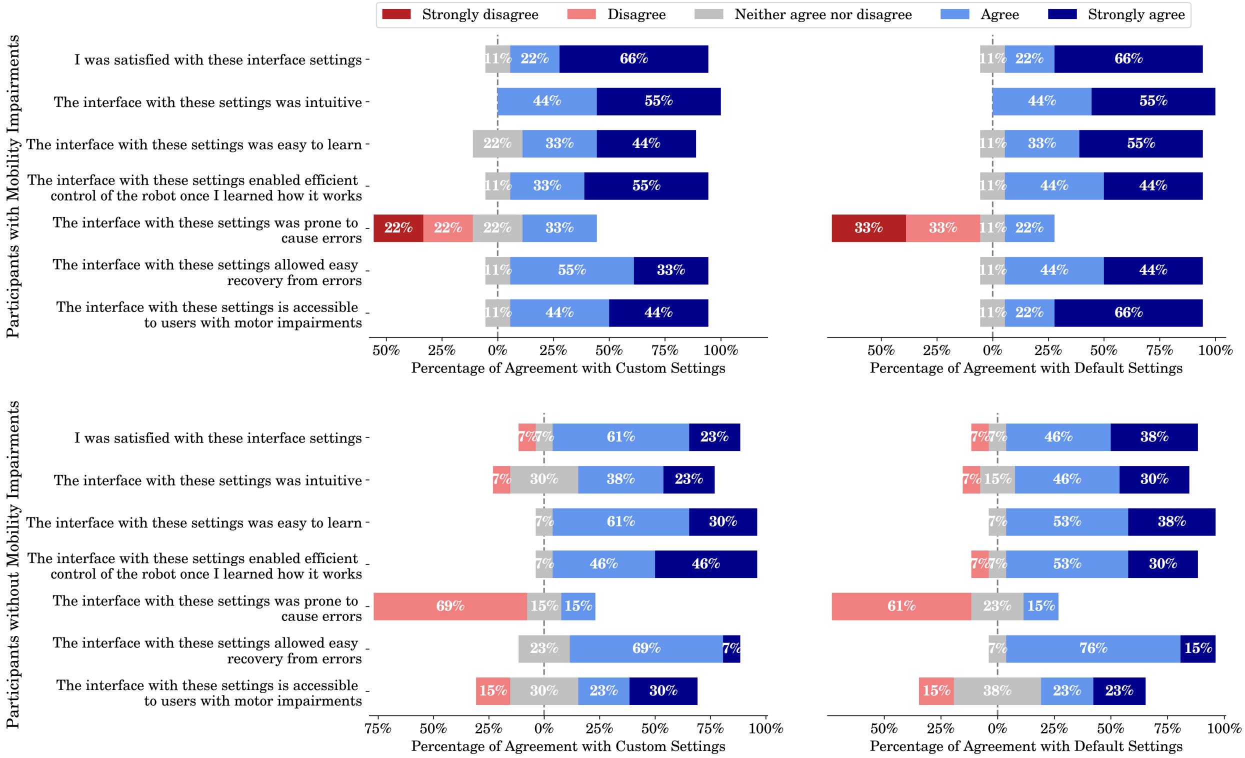


Figure 4.6: Participant agreement with statements about interface intuitiveness, efficiency, and accessibility.

4.6 *Summary of Findings*

4.6.1 Settings Preferences

User preferences in interface configurations varied. There was no single interface configuration that was more strongly preferred over another. Users with motor impairments did not choose the step actions mode due to the fatigue of repeated clicks. Some participants without motor impairments chose the step actions mode because they were concerned that continuous control modes would damage the robot. Additionally, P1 was not able to use the press-release mode with his head array. These findings confirm our hypotheses that there is no single interface configuration that satisfies all users' abilities and preferences (**H1**) and there are differences in preferences between participants with and without motor impairments (**H2**).

4.6.2 Task Performance

All users had faster task completion time and fewer clicks with the customized settings in the navigation mode but performed better the second time in the manipulation mode irrespective of which interface configuration they started with. This suggests that there was a learning curve, which is possibly due to the complexity of the interface controls in the manipulation mode. We believe if users had more time to familiarize themselves with the manipulation mode, they would have performed better with the customized settings. Additionally, users did not have a practice task that combined both navigation and manipulation modes. We noticed a learning curve associated with using both modes to complete a task. Overall, the number of errors was very low, all participants successfully completed Task 1 and 2 and all but two participants without motor impairments successfully completed Task 3. These findings partially confirm our hypothesis (**H3**) that users' task completion time, number of errors and clicks will be lower when using their customized settings.

4.6.3 Context Adaptation

Several participants wanted to switch between different settings when completing Task 3. For example, some participants wanted to use step actions mode when trying to pick up or drop the trash in the recycling bin. Some participants who selected the press-release mode realized that they could use it like the step actions mode with shorter clicks. This suggests that settings preferences can vary depending on the context of the task, and interfaces should allow for easy adaptation of settings to different contexts.

Chapter 5

ACCESSTELEOPKIT: A TOOLKIT FOR CREATING ACCESSIBLE WEB-BASED INTERFACES FOR TELEOPERATING AN ASSISTIVE ROBOT

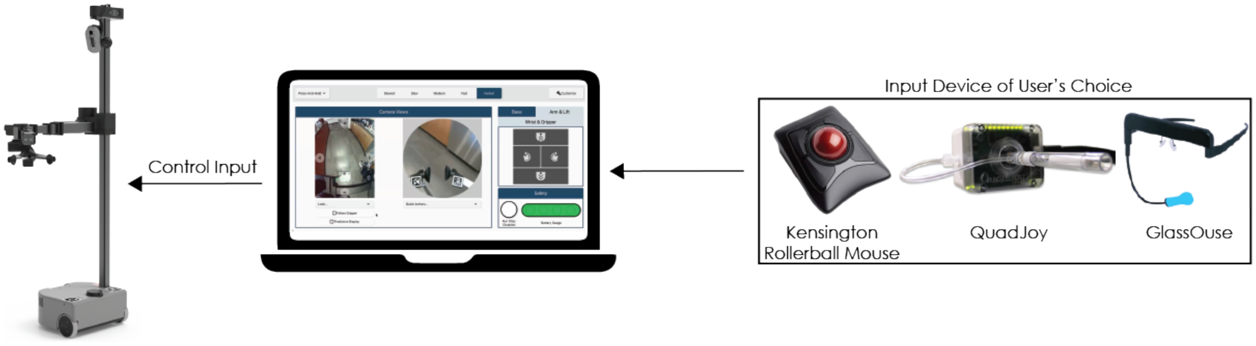


Figure 5.1: AccessTeleopKit (middle) controls Stretch (left) through cursor-and-click input. It can be used with any assistive device that can operate a computer such as a Kensington roller ball mouse, QuadJoy mouth-controlled mouse, and GlassOuse head mouse (right).

5.1 Robot System: Stretch 3

The Stretch 3 mobile manipulator (Fig. 5.1) is developed by Hello Robot [47]. It is similar to the Stretch RE1 and RE2 we used in prior work but with two notable upgrades. First, the arm has a 3 degree of freedom dexterous wrist and 1 degree of freedom gripper. Second, it has three cameras: a realsense D435if camera and wide-angle camera attached to a pan-tilt head and a realsense D405 camera mounted on the gripper. While we describe the toolkit features that are unique to the Stretch 3, the toolkit supports all versions of Stretch.

5.2 System Design

To address the various challenges that users have faced while testing prior iterations of the web interface, we propose the *AccessTeleopKit*, an open-source toolkit for creating custom

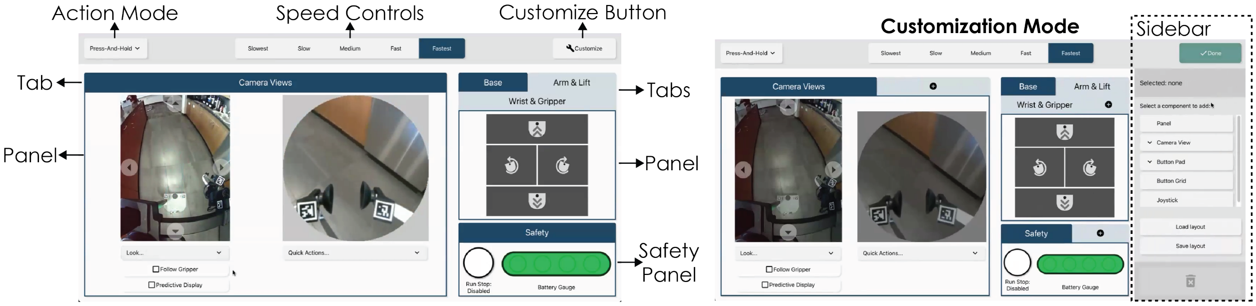


Figure 5.2: Overview of the standard layout (left) and customization mode (right) for the AccessTeleopKit.

and accessible robot teleoperation interfaces. Users can add, remove and rearrange components such as button pads and camera views and select between a variety of control modes. This level of customization allows users to create multiple layouts and choose the interface configuration that works best for them (**C7**). Below, we describe the design of our system and the justification for those design decisions.

5.2.1 Header

The header contains static components that are always available to the user.

Action Modes. There are three action modes that are available in the drop-down: (1) **Step Actions**, (2) **Press-And-Hold**, and (3) **Click-Click**. All action modes are applicable to all control displays. We developed these action modes to address **C1**. In the **Step Actions** mode, the robot moves for two seconds when the user presses the button or trajectory. The distance the robot moves is determined by the selected speed. In the **Press-And-Hold** mode, the robot moves when the user presses and holds the button or trajectory and stops when they release. Finally, in the **Click-Click** mode, the robot moves when the user clicks the button or trajectory and stops when they click again. The action mode applies to all control modes described in Section 5.2.2 (i.e. predictive display, joystick, button pads, and button grid). To ensure safety, when the user moves their cursor outside a button or trajectory region, the respective joint stops moving. In the prior version of the interface [68] the action modes were hidden in the settings menu. Participants requested to switch between action modes during the tasks (**C6**). To accommodate this need, we placed the action modes in the header as a drop-down, so users can quickly access it.

Speed Controls. The speed controls have 5 discrete speeds that the user can choose from. We specifically chose discrete controls rather than continuous input as interfaces that require moving the cursor to provide continuous values are less accessible [30, 11].

Customize Button. The customize button enables the customization mode. In this mode, all robot controls are disabled and a sidebar (described in Section 5.2.3) appears with options that allow users to add, delete, rearrange and modify the components in the layout (**C7**).

5.2.2 Layout

The layout includes panels and tabs which contain the user-selected customizable components. A customizable component is any component that can be added, removed or rearranged in the interface. At the top level, there are panels which can have multiple tabs that allow users to organize the layout as they see fit. The tabs can contain any combination of customizable components. We describe the available customizable components below.

In prior iterations of the interface, there were pre-defined *modes* that users could switch between: navigation and manipulation mode. The modes were structured as tabs and displayed a subset of camera views and controls that enabled the user to either drive the robot or move the arm and gripper for manipulation. While some users were content with switching between tabs, others preferred all controls on one page, or requested to change the order of the camera views and controls (**C4**, **C7**). We designed the layout architecture in a manner that allows users to construct the interface to meets their needs and preferences.

Button Pads. The buttons pads consist of a combination of buttons that control each of the robot's joints and are labeled with either icons or text depending on the user's choice. A button turns blue when its respective joint is moving, red when it reaches its joint limit, and yellow when that joint is in collision. Button pads were designed to follow Fitt's law which says that larger buttons in close proximity are easier and faster to reach with cursor movements [23]. All buttons pads consist of four to ten buttons. The larger the number of buttons, the smaller the size of the buttons. In prior studies, some users preferred having one all buttons in one button pad while others preferred multiple button pads, each controlling a different subset of joints. We provide several button pad configurations that users can choose from. Additionally, button pads can be overlaid on a camera view or placed in a tab as a separate component. While overlaying button pads on camera views is the most effective use of space, some users prefer separating the button pads and camera views (**C7**).

Camera Views. The interface has three camera views: overhead, realsense and gripper camera view. The multiple camera views help handle self-occlusion (**C2**) since it's impossible for the robot to be in a position where it occludes all cameras.

The **overhead** camera view displays a video stream from a wide-angle camera and has pan and tilt controls for moving the camera. This camera view has a set of buttons underneath it that the user can display or hide. The *predictive display* button overlays trajectories on the camera view when the user hovers their cursor over it. When the user clicks, the linear and angular velocity of the robot's base is set based on the length and curve of the trajectory. Longer trajectories result in greater linear velocity, and more curved trajectories result in greater angular velocity. This feature is inspired by the Beam telepresence robot, a commercial robot developed by Ohmni Labs. The *follow gripper* button automatically pans and tilts the camera to keep the gripper in view as the user moves the arm, gripper or wrist. Lastly, there are three quick *look* buttons that move the camera to desirable configurations. *Look ahead* moves the camera to look directly ahead of the robot, *look at base* angles the camera downwards to provide a view around the robot's base, and *look at gripper* rotates the camera to focus on the arm and gripper.

The **realsense** camera view displays a video stream from a realsense D435if camera. The camera is mounted on the same joint as the wide-angle camera. While this camera is pointed at the same scene as the wide-angle camera, it has a narrower field-of-view and is not distorted. Similar to the overhead camera view, it has pan and tilt controls, the follow gripper button, and the same quick look options. Additionally, it has a button to enable *depth sensing*. One of the biggest challenges users have faced in prior iterations of the interface was depth perception: estimating how close the robot needs to be to an object to be able to reach it with the robot's arm (**C3**). When enabled, all pixels in the image that are within the robot's reach are highlighted in blue. Users can use this feature to drive close enough to the target object before rotating to grab it.

The **gripper** camera view displays a video stream from a realsense D405 camera that is mounted on the robot's wrist. This allows the users to take a closer look at the object they are manipulating. This camera view has a set of *quick action* buttons underneath it that the user can display or hide. The *stow wrist* quick action button rotates the wrist inward to its stowed position. The *center wrist* quick action button rotates the wrist outward to be in line with the arm. These quick actions were implemented as they are common positions users would manually have to move to in prior iterations of the interface.

Joystick. The virtual joystick emulates a physical joystick for controlling the robot's base. This feature was introduced by Wojtowicz et al. [81].

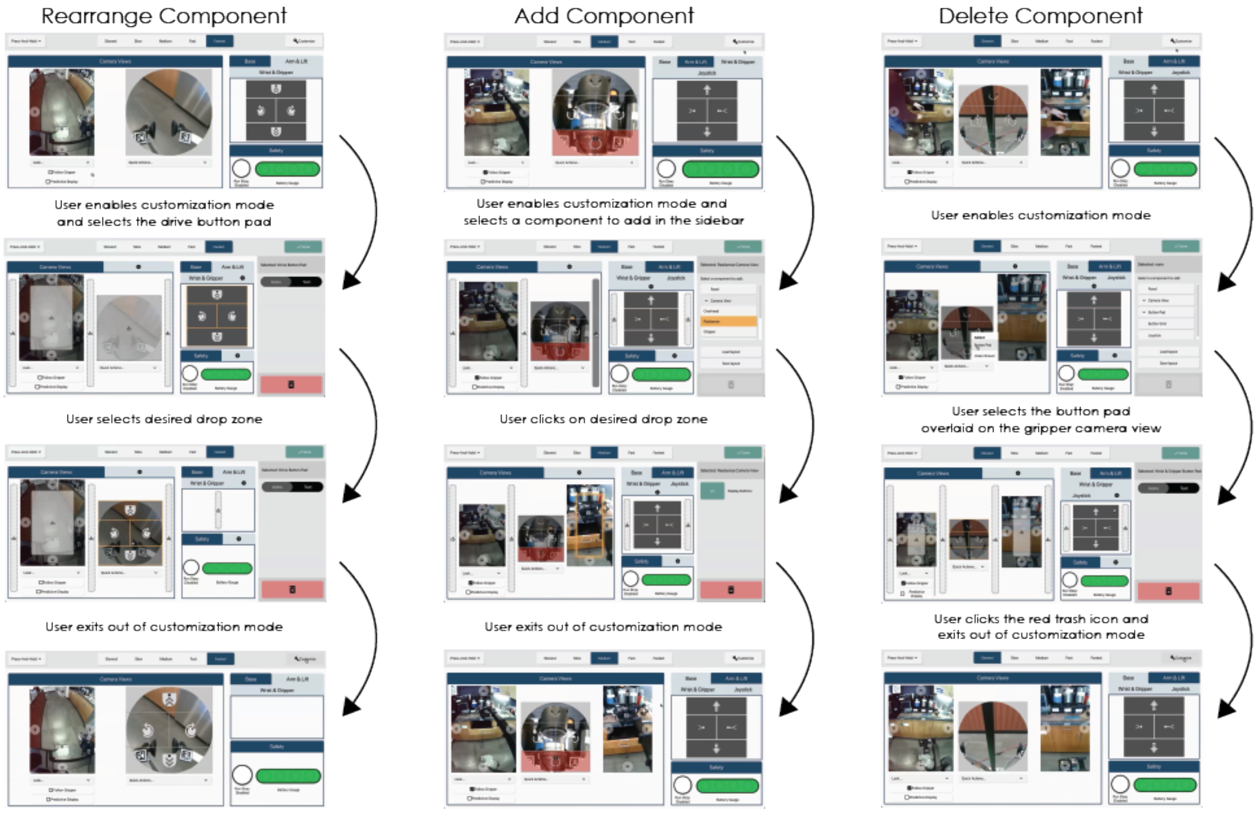


Figure 5.3: Example of how a study participant used the customization mode to (left) rearrange components in the interface, (middle) add a new component, (right) and delete a component.

Button Grid The button grid contains buttons for controlling all the robot's joints. Each row of buttons controls a different subset of joints: base, arm, wrist, and gripper. Similar to the button pads, the user can choose between text and icon labels and the color changes when the joint is moving, reached its limit or in collision. This feature was introduced by Wojtowicz et al. [81].

Safety Panel The safety panel contains the runstop button. When pressed, the robot's controls are disabled until the button is pressed again. The runstop button flashes when enabled in the interface to mimic the behavior of the physical robot. Additionally, there is a battery gauge that changes colors to represent the remaining charge. It mimics the battery gauge on the physical robot.

5.2.3 Sidebar

The customize button triggers the customization mode, which disables all robot controls and displays the sidebar. It contains a list of components that can be added to the layout. In this mode, the user can rearrange, add, and delete components. Additionally, users can add save and load layouts that they might use in different contexts.
Rearranging components To move a component that is already in the layout, the user can click on the component and then the drop zone they would like to move it to. Drop zones are gray regions that appear in a tab or on a camera view (if applicable). These signify the regions where the user can "drop" the component. In Fig. 5.3 a participant from the user study moves the button pad from the *Base* tab onto the gripper camera view in *Camera Views* tab.

Adding a component The user can then select a component from the sidebar, which will highlight orange when selected. Then the user can select the drop zone where they would like to "drop" the component. In Fig. 5.3 a participant from the user study adds the realsense camera view to the *Camera Views* tab.

Deleting a component To delete a component, the user can select a component in the layout and click the delete button in the bottom right corner. In Fig. 5.3 a participant from the user study selects the button pad that is overlaid on the gripper camera view and deletes it.

5.3 System Architecture

The AccessTeleopKit utilizes ROS2 (robot operating system), WebRTC (web real-time communication), NodeJS, and TypeScript. The system runs in a headless browser onboard the robot. The robot browser has access to the robot via ROS2, however, the operator can only send commands or receive information indirectly through the robot browser. We utilize WebRTC to establish a peer connection between the operator browser, which loads the AccessTeleopKit, and the robot browser. The robot browser uses rosbridge to connect to the robot via ROS2. Rosbridge translates JSON messages from the robot browser to ROS2 messages and vice versa.

When the AccessTeleopKit is launched on the robot, the ROS2 drivers and the robot browser are launched. The robot browser creates and joins a WebSocket room and waits for an operator to join. In a browser, the user can either go to an IP address when on the same network as the robot or a URL when accessing it remotely. We use N grok to establish a secure tunnel over the internet for remote use. When the user navigates to the IP address

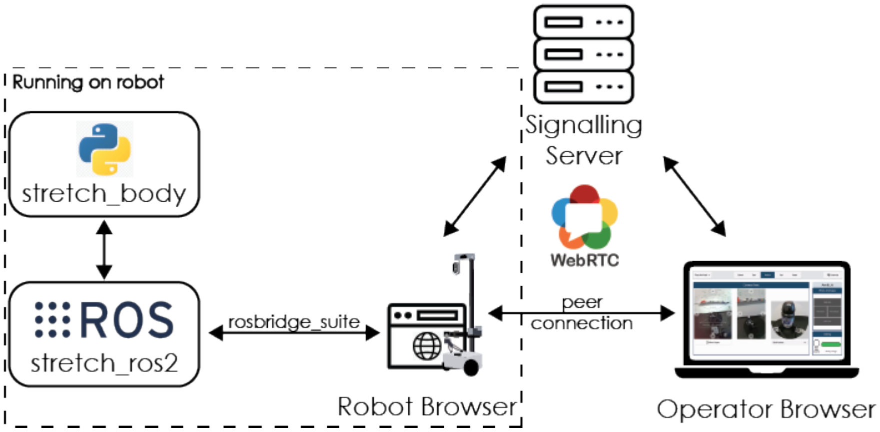


Figure 5.4: The software architecture of the AccessTeleopKit.

or URL, the operator browser joins the WebSocket room created by the robot browser and a peer connection is established. Note, only one peer connection between the operator and robot browser can be established. If another operator attempts to open the interface, the connection will be rejected.

Once a peer connection is established, the AccessTeleopKit will render the standard layout (Fig. 5.2) on the operator browser and the user will be able to control the robot. For example, assume the user clicks a button to drive the robot forward, the command is sent to the robot browser. This command is passed through rosbridge which translates the JSON message into a ROS2 message. The robot browser can also send information, such as joint limits and collision information, to the operator browser. When the user closes the browser, the peer connection is disconnected and another user can open the AccessTeleopKit. Note, in this work, we evaluate the AccessTeleopKit on the Stretch robot. However, **the front and back-end are decoupled to allow researchers to replace the back-end with a ROS2 ecosystem for another mobile manipulator**. Additionally, all our code is open-source[1] and officially supported by Hello Robot.

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[1] https://github.com/hello-robot/stretch_web_teleop

Chapter 6

IN-HOME EVALUATION OF THE ACCESSTELEOPKIT

6.1 Study Design

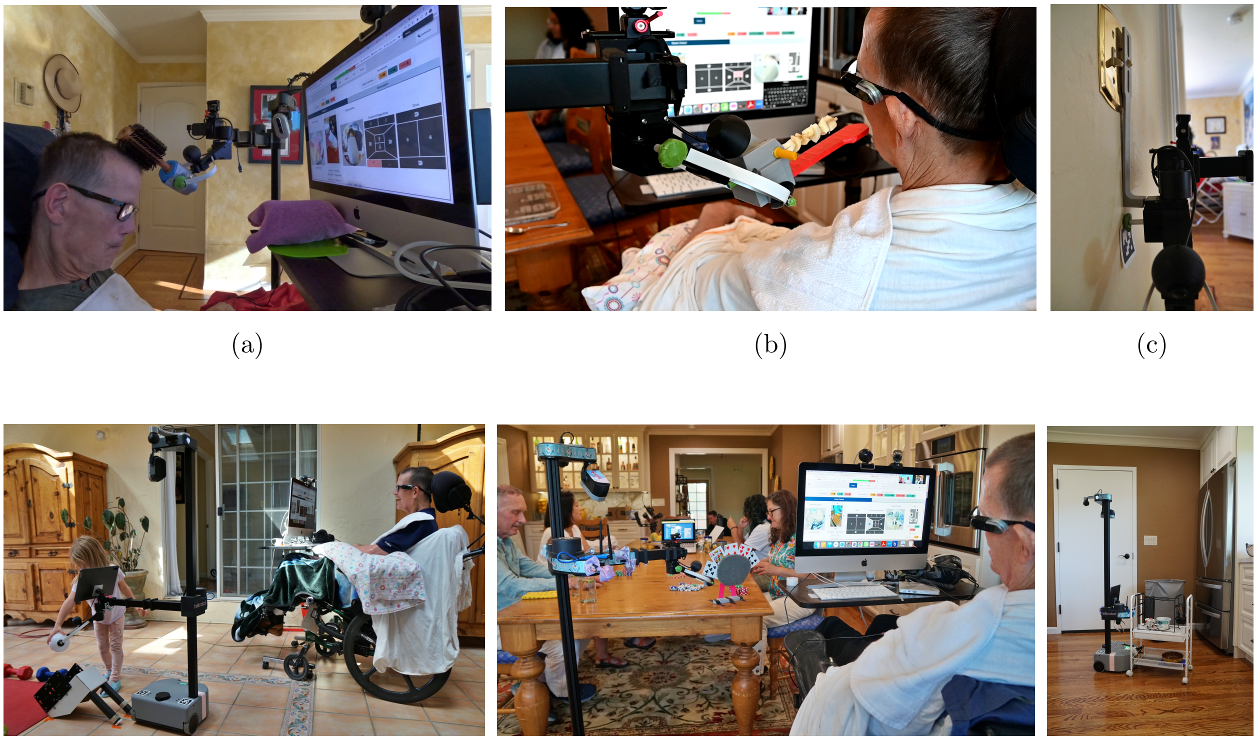
We conducted three one-week participatory design sessions where we tested the AccessTeleopKit, received feedback, and made iterations. We embedded Stretch, along with an engineer and OT, in Henry and Jane's home to support both of them in their daily activities. Prior to the deployment, we conducted interviews to identify the tasks that Henry and Jane would like Stretch to support them in. We developed a prioritized list of tasks and a timeline in which we would explore each task. Tasks were often repeated across sessions to test improvements to the AccessTeleopKit. Additionally, between each session, we developed tools for Stretch to support Henry's task performance and improved the AccessTeleopKit design and capabilities. For Jane, we iterated on a mobile prototype of the AccessTeleopKit that she could use to perform her caregiving tasks.

6.2 Tasks Performed by End-User

In this section, we describe the tasks Henry performed and divide them into three categories: (1) physically assisting self, (2) physically assisting a caregiver, and (3) engaging in social activities.

6.2.1 Physical Assistance for Self

Self-feeding. In prior explorations, Henry explored feeding himself soft foods, such as scrambled eggs and yogurt, with a spoon. In this exploration, we explored methods that would allow him to eat food items that he cannot eat with a spoon (e.g. bananas, cheese). Henry designed his own tool that can hold a skewer of soft cubed foods. After iterating on the design with an OT and engineers, we 3D printed the tool and added a silicone straw that Henry could use to push the food into his left molar, where he has the strongest bite. For safety reasons, there is a guard on the bottom of the tool to prevent the skewer from poking the user. Additionally, if any force is placed on the skewer, it slides backward to ensure it doesn't injure the user. With Stretch, Henry can pick up the tool and feed himself (Fig. 6.1b). In social settings, this reduces the burden on the caregiver and allows him to participate in



(a) (b) (c)

(d) (e) (f)

Figure 6.1: Henry Evans completing tasks independently by teleoperating the Stretch RE2 to (a) scratch his itches, (b) feed himself, (c) flip a light switch, (d) play with his granddaughter, (e) play poker, and (f) tow a meal cart.

social dining.

Scratching Itches. Due to Henry's paralysis, he cannot scratch his itches and can experience at least 3–4 itches a day. An OT adapted a hairbrush for Henry by affixing foam to its handle and placing it on a platform at a 45-degree angle. This optimal positioning enabled Henry to comfortably grasp it with Stretch and scratch his head (Fig. 6.1a). To make this task easier, Henry was able to prerecord poses and movements that he could play back.

Flipping a Light Switch. Flipping traditional light switches requires fine tune movements that can be difficult and time-consuming to perform when teleoperating a robot. To simplify this task, an OT and engineers developed an attachment to a light switch with a larger surface area for manipulating the switch (Fig. 6.1c).

6.2.2 Physical Assistance for Caregivers

Henry has a caregiving principle that states, *"No matter how much assistance a device provides to a [adult] patient, it will not be used regularly unless it also takes no time to either set up or use by the caregiver, and unless it makes the caregiver's life, a lot easier."* Therefore, one of his goals was to use Stretch to assist Jane with chores. Henry controlled Stretch to tow a laundry basket to the laundry room and a cart with his meal to his bedroom (Fig. 6.1f).

6.2.3 Social Participation

Playing with his Granddaughter. One task that was very important to Henry was to play with his three-year-old granddaughter. Jane shared that, *"Our granddaughter looks at Henry as an inanimate object and there's a sadness in that. [Henry] has shared with me how sad it is."*. With Stretch, Henry was able to play with his granddaughter for the first time. We mounted a tablet on Stretch's arm and displayed Henry's face in order to convey that Stretch was being controlled by Henry. There were three separate play sessions with Henry and Jane's granddaughter. In the first session, many family members were present to encourage the play. Despite her initial fear, she later engaged with Henry after observing him play with her family through Stretch. Together, Henry and his granddaughter decorated a box with stamps, played basketball, and had a relay race. She recognized Stretch as Henry, or "Papa Wheelie" as she calls him. In the second session, we took Stretch to her house. Henry remotely controlled Stretch from his home to build a fort with her. In the final session, she came back to the Evans's home, and they played a fishing game and bowling (Fig. 6.1d).

Playing Card Games. Henry expressed that he wanted to play card games with his family and friends. Before introducing Stretch, Henry had to be on a team with someone else but with Stretch he is able to play on his own team. To enable this interaction, an OT and engineer developed a cardholder with a handle for rotating it. Another player would place cards in the cardholder and Henry would extend or retract Stretch's arm to move the handle and rotate the cardholder. In a game like poker, where he may have to play or discard a card, Henry would rotate the cardholder until the desired card is centered and facing up. Another player would then take the card and play or discard it on Henry's behalf. By using Stretch and the cardholder, Henry attained a sense of accomplishment by winning against his friends and family in poker on his own (Fig. 6.1e).

6.3 Supporting the Caregiver

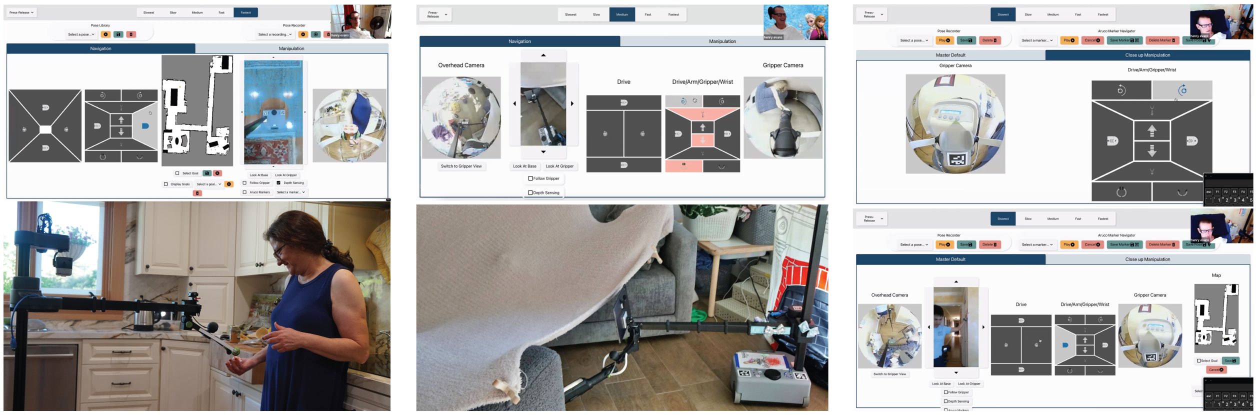
We primarily focused on how Stretch could support Henry in his daily activities; however, as Henry's caregiver principle states, it is equally important for the robot to support the caregiver. We conducted a few explorations on how Stretch could assist Jane as a caregiver and as an individual. One activity that was very important to Jane was personal training. Her sessions are typically held online over a Zoom call she joins through her laptop. This setup is not ergonomic as the screen is small, and she has to adjust the angle constantly. We enabled her personal trainer to connect to Stretch remotely so he could drive Stretch and use the arm and gripper to cue her. For example, he would place the gripper between her shoulder blades to cue her to squeeze them together.

Jane expressed that she wanted to use Stretch for her caregiving tasks. One important use case she described was to be able to check on Henry if he was home alone. More specifically, she wanted to lower the head of Henry's electric bed from a reclined position to lay down if he fell asleep, so his neck would not be in a flexed position. To enable Jane to perform this task, we developed a mobile prototype of the AccessTeleopKit. During the first session, we showed Jane how to use the AccessTeleopKit on a computer. We developed a list of features that she wanted to include in the mobile version. In the second session, we presented and iterated on wireframes with Jane. In the last session, we had Jane test the mobile prototype on her phone. She had Stretch autonomously navigate to the bedroom by clicking on the desired location in a map. She then teleoperated Stretch to press the buttons on a remote to adjust Henry's bed.

6.4 Findings

When asked to compare the toolkit prototype with previous iterations of the interface, the Henry said, *"Overall, the new software is very clean and logical. The [customization mode] is very helpful."* During the deployment, we iterated on the buttons' icons and size. Additionally, we iterated on several autonomous features, such as autonomous navigation. We do not describe these features in detail, as they are out of the scope of the AccessTeleopKit.

Henry created multiple interfaces that varied depending on the task he was performing. In one task, he handed Jane a container of jam in the kitchen while he was in his bedroom (Fig. 6.2a). He preferred having the controls for driving and manipulating split between two button pads. He primarily used the autonomous navigation feature for long range navigation. This was invoked by clicking on a goal location in the map. He relied on the realsense camera for short range navigation and the gripper camera for manipulation. Henry created a different interface when we took Stretch to his granddaughter's house (Fig. 6.2b). He was



(a) (b) (c)

Figure 6.2: Henry's customized interfaces for (a) handing jam to Jane, (b) playing with his granddaughter, and (c) turning his percussion vest machine on or off.

teleoperating Stretch from his home to play with his granddaughter remotely. He preferred to be in full control when using the robot around his granddaughter. In this scenario, he used all three camera views to have a better understanding of his surroundings. Lastly, when Stretch was in line-of-sight, he created a tab labeled *Close up Manipulation* that contained only the gripper camera view and button pad for controlling the arm (Fig. 6.2c). This tab was used when he did not need to drive. Since the robot was next to him, he did not need the other camera views. The *Master Default* tab had a combination of all the components he wanted to use when Stretch was not in line-of-sight. **The key finding from this deployment is that several factors influence customization beyond users' functional abilities and preferences, such as the task, context of the task, and whether the robot is in line-of-sight**.

Henry's main feedback, regarding the teleoperation features, was to reduce the clutter of buttons underneath the camera views, overlay the pan/tilt buttons on the realsense camera to save space, and to add the option of text labels. These improvements were made after the home deployment.

Chapter 7

IN-LAB EVALUATION OF THE ACCESSTELEOPKIT

7.1 Study on Customization Across Participants for Single Task

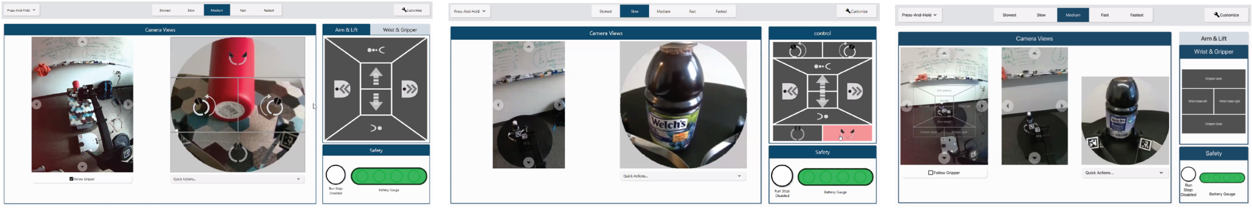
To more broadly evaluate the effectiveness of the interface, we ran an in-lab user study with individuals with motor impairments who are representative of our target population. We had 5 participants (P2, P3, P5, P7, P8) who had participated in our initial study where we evaluated customization (Table 4.2). The study lasted 90 minutes, and we compensated participants with a $100 Amazon gift card.

7.1.1 Procedure

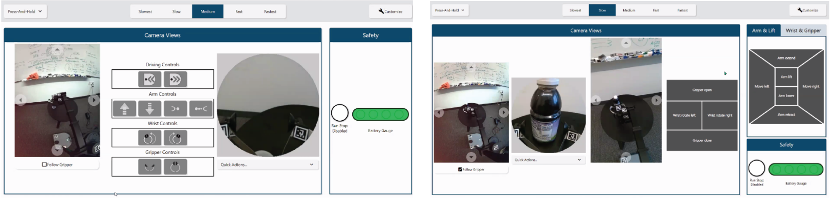
The study was conducted in an office room. Participants joined a Zoom video conferencing call with screen sharing capabilities and logged into the web interface, which displayed the standard layout (Fig. 5.2). Participants were located all around the U.S. and were not physically present.

To reduce the learning curve, we had participants focus on manipulation. We exposed all components except the joystick used for driving and the hid predictive display toggle. We provided all controls for the arm but limited the gripper controls to yaw rotation and the base controls to forward and backward movements.

We verbally instructed participants on how to use the interface. More specifically, we explained how every component works, how to customize the interface, allowed the participants to test each component until they were comfortable, and provided tips on how to successfully grasp objects. Next, we allowed participants to customize the interface to their liking. We then asked participants to complete a pick-and-place task where they picked up a bottle of juice off the ground and placed it on a table. The task was repeated at least twice or until they were satisfied with their customized interface. Participants were allowed to customize the interface at any time, including during the task or between attempts. We concluded the study with a questionnaire asking participants to rate their satisfaction with their customized interfaces and to describe their reasoning for the interface they created.



(a) Interface by P2 (b) Interface by P3 (c) Interface by P5



(d) Interface by P7 (e) Interface by P8

Figure 7.1: Final interface configurations created by participants in study evaluating customization for a single pick-and-place task

7.1.2 Findings

This study resulted in 5 unique interfaces shown in Fig. 7.1. **All participants liked having the ability to customize the interface**: *"I like how many options there are and that there isn't a rigid structure. You can really tear it apart and build it up how you want"* **(P2)**. Additionally, all participants found the interface accessible. One participant highlighted that being able to customize the interface *"takes away the number of clicks you have to do to achieve the action you want to do"* **(P3)**.

Some participants preferred having all the controls in one location, while others preferred separating them by joint group. P2 and P8 preferred having the gripper and arm controls separated: *"The button pad with all the controls was very crowded and wasn't easy to get used to"* **(P2)**, *"I like having the arm and gripper button pad separate so that I don't mix the buttons up"* **(P8)**. P3, P5, and P7 preferred having all the buttons in one place. P7 said, *"it made it easier to accomplish the task without clicking around"*. Note, multiple participants left elements from the standard interface in their customized interface even though they did not use them. P1 and P5 did not use the tab titled *Wrist & Gripper*, and P3 did not use the tabs titled *Arm & Lift* and *Wrist & Gripper*. These participants did not find these components bothersome, so they did not delete them from the interface and ignored them.

Some participants preferred icons, while others preferred text labels. P2, P3, and P7 found the icons intuitive while P5 and P8 did not: *"Without the text options I would have been confused about what the icons do"* **(P5)**.

All participants had different preferences on the placement of the controls. P2 preferred some of the controls overlaid: *"I was looking at the [gripper] camera anyways to pick up the bottle and thought it was more intuitive to have the controls there."* Meanwhile, P5 preferred all the controls overlaid on the camera view she used the most. P4 preferred having the button grid in the middle, as that's what made most sense to her. However, P3 preferred it on the side: *"I started with the controls between the camera views, but I found that distracting constantly having to look back and forth, so I liked it better on the side"* **(P3)**. P8 preferred having the button pads side-by-side.

While all participants used the gripper camera view, there were varying preferences between the overhead and realsense camera view. The overhead and realsense camera view offer the same perspective, however, the overhead provides a wide-angle distorted view while the realsense provides a narrower undistorted view. P2, and P7 preferred the overhead camera view over the realsense camera view: *"The realsense seems redundant with the [overhead] camera, so I didn't want to crowd the screen. I like that you can see way more [overhead] camera"* **(P2)**. P3 chose the realsense camera view over the overhead camera view, as she found it easier to orient the robot. Meanwhile, P5 and P8 preferred having all camera views to have both a better understanding of their surroundings, but also take a closer look at the object they were manipulating.

P5 and P7 noted that their customized interface was easier and faster to use than the prior iteration they tested that had a fixed layout (Chapter 4; [68]). This suggests that customization may have an impact on learning curve, however, we cannot say for certain as our study was not designed explicitly to explore this.

7.2 Study on Customization Across Multiple Tasks

In this study, we were interested in how the interface would evolve across multiple tasks for a single user. We conducted this study with a 1 participant (Male) with motor impairments who is representative of our target population. He cannot reach his arms above his waist, his legs fixed straight, has limited finger movement. The study lasted 2 hours, and we compensated the participant with a $150 Amazon gift card.

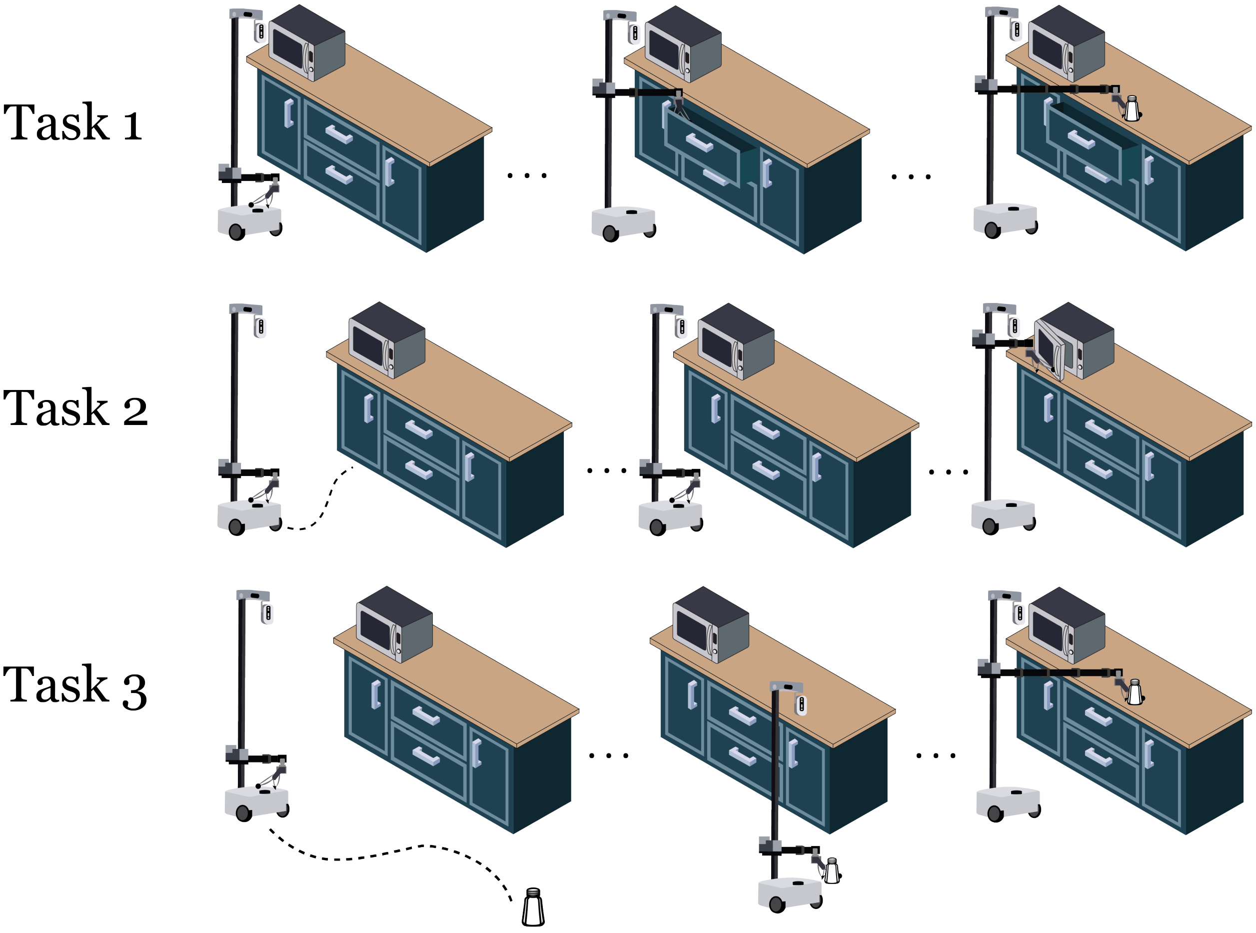
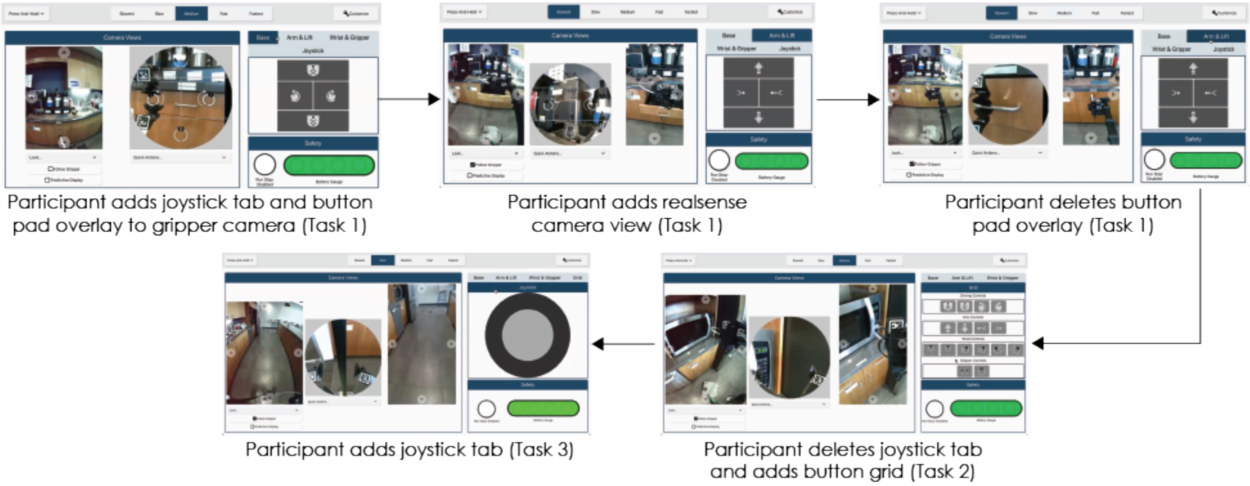


Figure 7.2: The tasks for the study on customization across multiple tasks: (top) taking a salt shaker out of the drawer and placing it on a counter, (middle) opening a microwave, and (bottom) picking a salt shaker off the ground and placing it on a counter.

7.2.1 Procedure

This study was conducted in a kitchen environment. The participant joined a Zoom video conferencing call with screen sharing capabilities and logged into the web interface. The participant was located in the U.S. and was not physically present.

The participant had previously tested an earlier iteration of the interface and has some familiarity with how to use the interface. We exposed all elements in the interface as learning curve was not a concern. We verbally instructed the participant on how to use the interface and allowed him to test each component until he was comfortable. We asked him to customize


Participant adds joystick tab and button pad overlay to gripper camera (Task 1)

Participant adds realsense camera view (Task 1)

Participant deletes button pad overlay (Task 1)

Participant deletes joystick tab and adds button grid (Task 2)

Participant adds joystick tab (Task 3)

Figure 7.3: Evolution of the interface in study on customization across multiple tasks

the interface to his liking and complete three tasks two times each. He was allowed to customize the interface at any time including during and between tasks. The tasks (Fig. 7.2) started with pure manipulation and gradually introduced navigation:

Task 1–The participant opens a drawer, picks up a salt shaker in the drawer and places it on the counter. The task only required moving the arm, wrist and gripper. The robot's base was positioned such that the arm was in line with the drawer's handle.

Task 2–The participant opens the microwave door. This task required positioning the robot's base such that it was in-line with the microwave, and coordinated base and arm movements to open the microwave door.

Task 3–The participant drives from the kitchen to a table, picks up the salt shaker, drives back to the kitchen and places the salt shaker on the kitchen counter. This task involved both navigation and manipulation.

7.2.2 Findings

Unlike the lead user in the home deployment who created multiple interfaces, which varied depending on the task and context of the task, this participant opted for a single layout that was optimized for all tasks. The evolution of the interface during the study is shown in Fig. 7.3. For Task 1, he added the joystick and the wrist & gripper button pad overlay on the gripper camera. He later added realsense camera: *"I added the [realsense camera view] because I wanted a better view of the arm and see it up closer. The wide angle would be better for driving, but the realsense was better for manipulating."*. Later, the participant found the overlaid button pad distracting and removed them. During Task 2, he removed the joystick controls as he was not using them and added the button grid which contained all the robot controls: *"I knew it wouldn't be a linear movement but many coordinated movements between different joints. I wanted everything to be in one place, which is why I chose the [button] grid, so I didn't have to switch between tabs"*. Finally, for Task 3, he re-added the joystick controls, however, ended up using predictive display over the joystick: *"I liked how intuitive how the predictive display was. The predictive display didn't switch my attention between the camera controls and the joystick"*. The participant added that he would likely delete the tabs labelled *Base*, *Arm & Lift*, and *Wrist & Gripper* for future tasks and that he could see the interface changing more if he continued to use it. **The key takeaway from this study is that interfaces can evolve over time, implying customization is not a one-time event but rather an ongoing process.**

Chapter 8

UNDERSTANDING OCCUPATIONAL THERAPISTS' PERSPECTIVES & BARRIERS FOR IMPLEMENTING ASSISTIVE TECHNOLOGY AND ROBOTS

The involvement of robotics researchers and developers on the project was also critical, given that the Stretch robot is currently a research tool. The team developed new capabilities, adapted the robot to the user's home (e.g., by creating a robot map), and developed the customizable and accessible interface for the user to teleoperate the Stretch. Ultimately, the collaboration between the OT and roboticists resulted in transformative outcomes for Henry. However, empowering many more people with motor limitations will require getting the roboticists out of the loop, by designing robots that can be used, customized, and deployed by OTs. Further, we need to ensure that OTs are aware of the existence of robots like the Stretch, and they have an accurate understanding of its capabilities so they can prescribe it appropriately. To understand what are barriers standing in the way of OTs prescribing physically assistive robots and inform the design of robots for the OT toolbox, we interviewed and surveyed OTs as described next.

8.1 Interview Study with Occupational Therapists

To inform the design of physically assistive robots for the OT toolbox, we turned to the OTs. We designed an interview (Appendix E) with the specific goals of (1) understanding current barriers OTs face when learning and prescribing existing assistive technology to their clients, (2) assessing their knowledge of and thoughts on existing assistive robot platforms, (3) gaining insights on use cases and potential target populations for the Stretch robot, (4) collecting feedback on the current method for operating the Stretch robot, and (5) understanding their perceived role in implementing Stretch as an intervention for their clients. The interviews were conducted over Zoom and lasted about 90 minutes.

8.1.1 Participants

We recruited 10 OTs (Appendix A) with experience working with adult clients with motor impairments and varying levels of experience with ATs and assistive robots. All participants live in and are licensed to practice in the US. Participants were recruited by a member of the research team who is a licensed OT, and their OT credentials were verified. Participants were compensated with a $75 Amazon gift card at the completion of the study.

8.1.2 Procedure

Our interview consists of 5 sections where we ask questions about (1) general assistive technology, (2) assistive robots, (3) the Stretch robot (4) the teleoperation interface for the Stretch robot, and (5) on-boarding.

General Questions about Assistive Technology

The goal of this section is to gain insight on OTs experience and perspective on AT and any barriers they face using, understanding or prescribing ATs. Some questions include (1) *What ATs do you use?*, (2) *What are the key factors you consider when assessing the suitability of an AT for a specific client?*, (3) *What challenges do you face when learning how to use new ATs?*, and (4) *Do you have any specific concerns about prescribing ATs?*

Questions about Assistive Robots

In this section, we want to understand the OTs knowledge, perceptions and expectations of robots. Some questions include (1) *What is your understanding about robots, and how are they different from other ATs?*, (2) *What would you expect a robot to be able to do for your client(s)?*, (3) *Do you have any concerns about prescribing robots to your clients?* Next, we present 3 existing assistive robot platforms: the Labrador Retriever robot (Fig. 8.1.a), the Kinova Jaco arm (Fig. 8.1.b), and the Stretch 3 (Fig. 8.1.c). For each robot, we have the participants watch videos that showcase its abilities and then ask the following questions: (1) *Given the robot's abilities do you think it would be useful to any of your clients?*, (2) *Do you think your clients would like this kind of robot in their home?*, and (3) *How likely are you to prescribe this robot to your clients? (1-5).*

Case Study of the Stretch Robot

We show participants a video the lead user from our home deployment using the Stretch robot in his home. We then ask participants to construct an occupational profile for a client they think would benefit from using Stretch. To guide the participants, we adapted questions from the American Occupational Therapy Association template. Some of the guiding questions include: (1) *what are your client's occupational needs?*, (2) *what barriers*

(a) Labrador Retriever Robot (b) Kinova Jaco (c) Stretch 3

Figure 8.1: The robots we present to the OTs during the interview.

are affecting their success in their desired occupations, and (3) *what factors are supporting engagement in desired occupations, and what aspects are inhibiting engagement.*

Testing the Stretch Tele-Operation Interface

We give participants access to the teleoperation interface for controlling the Stretch robot. The Stretch robot was located in the lead researcher's home, and participants opened the interface on their laptops to control the Stretch robot remotely. We taught participants how to use the interface and had them perform a simple task of picking a bottle off a table to better understand how the interface works. We then ask the participant how they would change the interface to accommodate the client from the occupational profile developed in the previous section. If the interface's current customization options support the participant's requested changes, we perform the customization. We want to gain insight into whether the participant believes they can perform this customization, if it is intuitive, and what other customization options we will have to implement to accommodate various clients.

Questions about On-Boarding

In this last section, we asked the participants questions about what they would like to see in a potential on-boarding process. Some questions include: (1) *Could you describe what you'd expect for each step and why?*, (2) *Where do you see OT's role have the most impact? Do you want to be involved in ordering the robot, setting it up for your clients, going to the* *client's home, etc.?*, and (3) *How much should the client be involved during the on-boarding experience?*.

8.2 Online Survey with Occupational Therapists

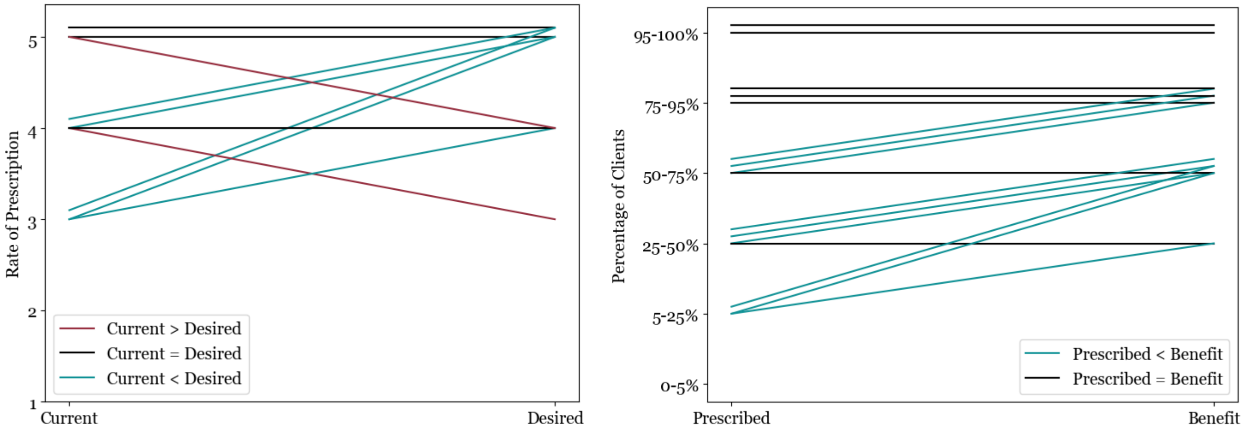
In order to increase our reach to more OTs, we designed an online questionnaire with similar questions as the interview with a reduced scope (Appendix F). While we faced difficulty recruiting participants for a lengthy Zoom interview, we were able to recruit OTs for the questionnaire by emailing it to participants. The questionnaire took approximately 30–45 minutes to complete, as opposed to the full 90 minutes that the interview took.

8.2.1 Participants

We recruited 16 OTs (Appendix A) with experience working with adult clients with motor impairments and varying levels of experience with ATs and assistive robots. Participants were recruited by a member of our research team, who is a licensed OT, and through referrals from their colleagues. Participants were compensated with a $40 Amazon gift card at the completion of the study.

8.2.2 Procedure

We emailed a Google form to the participants. The form consisted of the first three sections of the interview we conducted (Section 8.1). We omitted the last two sections on the teleoperation interface and on-boarding, as we could not demo the interface in an online survey. Additionally, we made two major changes to the existing questions. First, we altered the questions where we collected quantitative data. More specifically, in the interview, we asked participants to rate the *likelihood of prescription* of ATs and the assistive robots we presented. However, at the conclusion of interviews, we wanted to understand what percentage of clients the OTs believed would benefit from the technology and how willing they are to prescribe the technology to that client population. We rephrased our questions to capture this information. Second, we removed the guiding questions for developing the occupational profile of a client that could benefit from Stretch. Instead, we simply asked participants to describe such a client in whatever level of detail they felt was necessary.



(a) Responses from Interview

(b) Responses from Survey

Figure 8.2: (a) Interview participants ratings of current rate of prescription of ATs and desired rate of prescription of ATs. The red, black, and blue lines denotes participants who want to prescribe ATs less frequently, at the same rate, and more frequently respectively. (b) A line plot showing participant responses for the percentage of clients they currently prescribe ATs and the percentage of clients they believe would benefit from ATs. The blue lines denote participants who believe a higher percentage of clients would benefit from ATs and the black line denotes participants who believe the percentage of clients being prescribed ATs is equivalent to the percentage of clients that would benefit.

8.3 Findings

8.3.1 Understanding Barriers with Existing Assistive Technology

Perspectives on Assistive Technology

In the interview, we asked participants to rate how often they currently prescribe ATs and how often they would like to prescribe ATs on a 5-point likert scale (Fig. 8.2a). 3/10 participants want to keep their current rate of prescription, 5/10 participants want to increase their rate of prescription and 2/10 participants want to reduce their rate of prescription. One participant noted that she is concerned that ATs would result in loss of functional abilities and increase reliance on the AT: "*I want to give people whatever they need to be as independent as possible. I also don't want them to use something if they don't necessarily need to use it, because I feel like people will rely on it and then lose the ability to do it without it, if they were capable of it.*" (**I10**). Another participant stated that they would prefer society to adapt to individuals with disabilities: "*I wish we had a society and lived in environments that adapted for [people with disabilities], so that [ATs] and financial burdens became less necessary for the people I was working with*" (**I6**).

In the survey, we modified the questions to understand if the current prescription rate matches the perceived percentage of clients that would benefit from ATs (Fig. 8.2b). 7/16 participants stated that the percentage of their clients being prescribed ATs matches the percentage of clients they believe would benefit from ATs. Whereas 9/16 participants stated that a higher percentage of their clients would benefit from ATs than the percentage of clients currently being prescribed ATs. Additionally, we asked participants to rate how often they would like to prescribe ATs on a 5-point likert scale. All participants that believe a higher percentage of clients would benefit from ATs want to prescribe ATs more often.

Barriers Preventing the Prescription of ATs

The most common barrier OTs face when prescribing ATs is **cost and denial/lack of insurance coverage** (15/26). Several OTs noted that ATs are expensive and sometimes insurance does not cover it or only covers a portion of cos. Participant **I10** specifically noted that while she has some clients who are willing and able to pay full-price for ATs, she also has clients from lower socioeconomic backgrounds who will not even consider an AT if insurance does not cover it. **Socioeconomic constraints** are another barrier expressed by multiple OTs (3/26). Additionally, **buy-in from clients** on what they are willing to trial and invest in is another barrier (5/26). This can be because clients do not want to add additional technology to their routine (1/26) or clients, particularly older adults, that have lower tech literacy level find it difficult to learn how to use ATs (3/26). Furthermore, OTs may not prescribe ATs because they are not suitable for clients with **cognitive impairments** (1/26), **procuring the device is too difficult** (2/26), teaching clients to use the AT and incorporating it into their routine takes too much **time** (2/26), the **device is too large** and won't fit in the clients' home (2/26), or they **don't know of all the options or have a deep enough understanding of how the AT works** to confidently prescribe it to their clients (4/26).

Factors for Assessing the Suitability of an AT for a Client

The main factors that are considered before prescribing an AT to a client are the client's **cognitive abilities** (14/26), **physical abilities** (8/26), their **goals** (6/26), their **motivation** to learn how to use a new device and incorporate it into their daily routine (7/26), and whether they have **family/caregiver support system** to help set up and maintain the

AT (9/26). Additionally, some OTs have noted that they look at the client's **financial status** to ensure they can purchase the device (3/26) and pay for any necessary maintenance or upgrade costs (1/26) as well as whether the **AT is suitable for the client's home** (3/26). More specifically, they evaluate whether the AT will fit in the client's home and if the necessary modifications have been made to incorporate the AT. Furthermore, **technology acceptance** (1/26) and **ease-of-use** of device (1/26) are assessed. The **longevity of the client's impairments** (1/26) and the **adaptability** (2/26) of the device to clients' changing needs can impact whether an AT is prescribed. In a rehab setting, where the goal is to regain the baseline functional skills prior to the injury or illness, the AT must be able to adapt to the client regaining their functional skills. Similarly, the AT must be able to adapt to a client that is losing functional skills due to an illness, such as ALS.

Learning to use Assistive Technology

The most popular methods in which the participants currently learn to use ATs is through **hands-on testing** (15/26), **learning from colleagues** (7/26), **demos from vendors** (8/26), and **continuing education units (CEUs)** (5/26). Other methods include **internet searches** (1/26), **social media** (1/26), **instruction manuals** (1/26), and **sponsored training** (1/26). Hands-on testing (10/26), live demonstrations (12/16), CEUs (4/26), and training from vendors (3/26) are the ideal methods in which participants want to learn to use ATs. The majority of the participants spend their own time and money purchasing and learning to use ATs. In order to alleviate this burden, the participants would like the ability to **loan and trail the ATs** (2/26) and have **sponsored training** from their employers (1/26).

Challenges during AT Implementation

Participants noted several challenges during AT implementation. It takes a significant amount of **time** to properly implement the AT (2/26). This includes **convincing the client** that the AT will help them achieve their goals (2/26), **educating the client** on how to properly use the AT (3/26) and **educating the caregiver** (1/26) on how to set up and support the client when using the AT. Client and caregiver education can be difficult and time-consuming because **ATs tend to be complex** (3/26) and can lead to **frustration** (2/26). Additionally, changes in the client's abilities can make the AT less usable or render the need for a more advanced AT if the **AT is not adaptable** (1/26).

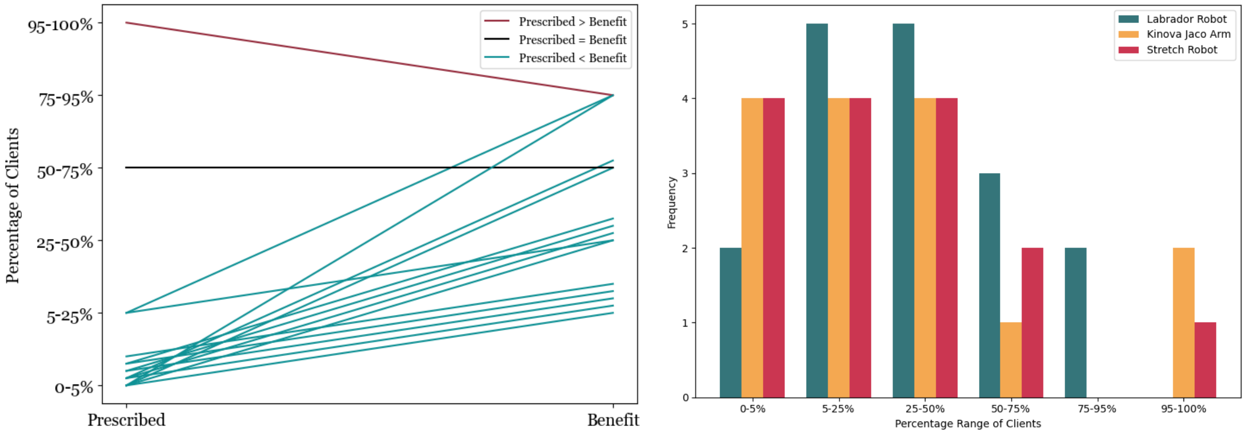
Reasons for AT Abandonment

AT abandonment is a frequent occurrence. One reason is due to **frustration** (5/26) often due to the **complexity of the AT** (4/26) leading to a long period of time taken to complete the task: "*[clients] become frustrated because they forgot what I trained them to do, or they preferred to have a caregiver do it for them out of length of time needed to do the task with a device*" (**S1**). Second, there is a **social stigma** around using ATs (4/26). Participant **I9** mentioned that some of her clients don't want to look different and will not use an AT even if it impacts their safety: "*So if it's something like walkers, especially, there's a certain association with them for being for [older adults], and so [my clients] just don't use it. They don't really want to use it and that impacts their safety*" (**I9**). Participant **I9** has tried to tackle this issue by personalizing ATs for her client to make it "*feel like it's an extension of their personalities and not just a tool.*" Third, the **AT is not a right fit** for the client (4/26): "*It can be that the AT prescribed/ used was never the right fit to begin with, which could be a result of poor communication and understanding of the needs. Abandonment could also occur when one initially had wrong understanding about the capability of the tool, and it fails to realize on the imagined capability. This is in part poor marketing of the device*" (**S4**). Additionally, the **ATs that are not able to adapt** to the client's changing abilities, leading to poor fit down the line (5/26). Finally, clients' **lack of desire to consistently use the AT** can lead to abandonment (4/26). This can be due to the AT being too **difficult to set up** (1/26) and **maintain** (1/16) or the **device is not suitable for the client's home or does not fit into their routine** (1/26).

8.3.2 Initial Perceived Benefit, Concerns, and Expectations of Assistive Robots

Perspectives on Assistive Robots

3/10 participants we interviewed had experience using assistive robots in their practice, whereas 7/10 participants had no experience and little to no knowledge about assistive robots. We asked participants to rate the likelihood they would prescribe assistive robots on a 5-point likert scale. The participants who had no experience with assistive robot, on average, rated that they were unlikely to prescribe assistive robots (M=2, SD=1.14), whereas participants with experience using assistive robots were more likely to prescribe assistive robots (M=4, SD=1). In the online survey, 4/16 participants had experience prescribing assistive robots and 12/16 participants had little to no knowledge about assistive robots. We asked participants to select the percentage they currently prescribe robots to and the percentage of clients they believed would benefit from an assistive robot (Fig. 8.3a). 14/16 participants believe that a higher percentage of clients than they're currently prescribing to



(a) Initial Perceived Benefit of Assistive Robots (b) Perceived Benefit of Assistive Robot Platforms

Figure 8.3: (a) A line plot showing participant responses for the percentage of clients they currently prescribe assistive robots to and the percentage of clients they believe would benefit from assistive robots. The blue lines denote participants who believe a higher percentage of clients would benefit from assistive robots, the black lines denote participants who believe the percentage of clients being prescribed assistive robots is equivalent to the percentage of clients that would benefit them, and the red line denotes participants who believe a lower percentage of clients would benefit from assistive robots than the percentage currently being prescribed. (b) A bar chart illustrating the survey responses for the distribution of percentage of clients that would benefit from the three assistive robot platforms: Labrador robot, Kinova Jaco arm, and the Stretch robot

would benefit from assistive robots. Additionally, we asked participants to rate how often they would like to prescribe assistive robots on a 5-point likert scale. 2/16 participants who currently prescribe assistive robots in their practice are satisfied with their current level of prescription. 11/16 participants who believe a higher percentage of their clients would benefit from assistive robots want to prescribe them more often. However, 3/16 participants do not want to prescribe assistive robots even though they believe more clients could benefit from them due to their own lack of knowledge about robots. In general, participants identified **lack of education and knowledge** on assistive robots (14/26) and **cost** (10/26) has the biggest barriers for prescribing assistive robots.

Expectation of Assistive Robot Capabilities

The participants believe that assistive robots should assist with **ADLs**, (7/26) such as **feeding** (3/26) and **grooming** (3/26), and **IADLs** (2/26). Many participants work with older adults with cognitive impairments and said that robots should be able to **ensure safety** (3/26) of the client by **preventing falls** (2/26) and **monitoring appliances** (2/26) as well providing **reminders** (4/26) and assisting with **medication management** (3/26). Other participants said that robots should generally **increase independence** (3/26), **improve the client's quality of life**, and **increase their performance and satisfaction in their desired occupations** (1/26).

Concerns with Prescribing Assistive Robots

OTs biggest concern with prescribing assistive robots is **cost** (11/26). More specifically, whether insurance would cover the robots or if clients would have to pay for it out-of-pocket. Additionally, OTs are concerned with their **lack of knowledge about robots** (5/26) and whether **knowledge translation** can keep up with the pace of development: "*assistive robotics are actively being developed and improved, so there is relatively little established best practice–even if we were to implement something of sorts the pace of development will likely outpace the time it would take for knowledge translation*" (**S4**). Beyond that, participants are concerned about older adult clients' level of **technology acceptance** (2/26) and their **ability to understand** how to use the robot (3/26), **safety** (4/26), and **privacy** (3/26).

8.3.3 Perceptions on Existing Assistive Robot Platforms

In this section, we summarize the findings on participants' perceived benefits and concerns of three existing robot platforms: the Labrador robot, Kinova Jaco arm, and Stretch robot.

Perceived Benefits

During the interview, we asked participants to rate the likelihood of prescribing the Labrador robot (M=3, SD=1.12), Kinova Jaco arm (M=3.5, SD=1.58), Stretch robot prior to viewing the case study video (M=4, SD=0.8), and the Stretch robot after viewing the case study video (M=4.6, SD=0.89) on a 5-point likert scale. While all participants found that the Labrador robot was useful, participants noted that the robot's form factor was limiting in that it could not pick up items (2/10). Participants, on average, found the Kinova Jaco arm slightly more useful because of its ability to pick up items. However, noted it was limited because it cannot operate independently of a wheelchair (2/10) and that the robot seemed more useful for individuals with very limited mobility but not for older adults or people with higher functional abilities (3/10). Participants, on average, found Stretch to be more useful than the Labrador robot and Kinova Jaco arm because of its ability to do many different tasks (1/10), ability to assist many different client populations (2/10), and because it can operate independently: "*I like that it's own separate entity in comparison to the [Kinova Jaco arm]. Compared to the [Labrador robot] it does more physically for the person* (**I1**)." After watching the case study video on our most recent deployment of Stretch in the older adult couples home, more participants were more willing to prescribe Stretch not only because of the difference it made in lead user's functional everyday activities (2/10) but also because of the caregiver involvement (3/10).

In the survey, we asked participants to select the percentage range of participants who would benefit from each of the assistive robot platforms (Fig. 8.3b). Majority of the responses fell in the 5-25% and 25-50% range. 5/16 participants noted that these robots are most suited for clients with no cognitive impairments. 13/16 participants reported that they work with older adults with mild to severe cognitive impairments and may have potentially contributed to the lower percentage of clients that would benefit. Additionally, 9/16 participants believed the Labrador robot and Stretch robot are beneficial for individuals with motor impairments, and 14/16 participants believed so for the Kinova Jaco arm. 11/14 and 7/9 participants emphasized the usefulness of the Kinova Jaco arm and Stretch robot, respectively, for people with *significant* motor impairments. 2/16 participants primarily work with individuals with moderate to severe motor impairments and noted that the Kinova Jaco arm and Stretch robot would benefit a larger percentage of their clients.

Concerns

Participants were concerned with being able to teach their clients with cognitive impairments how to use the Labrador robot (3/26) and some were specifically concerned that their older adults clients would lose balance when bending over or shifting weight to pick up items the robot delivers (2/26). One participant was specifically concerned with loss of functional skills: "*Similar to a lift chair, I might not always recommend it because there is still benefit in still practicing those functional skills as allowed*" (**S16**). Participants were mainly concerned with the high cognitive workload to operate the Kinova Jaco arm (3/26) and the Stretch robot (3/26) since they both use teleoperation interfaces. Additional concerns were ease of use (3/26) and setup (2/26) for the Kinova Jaco arm and time required to train the client (2/26) and privacy (2/26) for the Stretch robot.

8.3.4 Summary of Potential Client Profiles for Stretch

We asked interview participants guiding questions to develop a summary of an occupational profile for a client that would benefit from having Stretch in their home (Appendix D). All clients they described had some level of motor impairments, are cognitively intact, and require varying level of caregiver assistance in completing ADLs. The proposed client's target outcomes' included increasing independence in ADLs (7/10) and socialization (4/10), general increase in independence (1/10), reducing burden of care (1/10), and agency over the level of care provided (1/10). Participants who described client roles as a "family person", "parent", or "grandparent" specifically mentioned the clients' desire to contribute in supporting their family (7/10). We asked survey participants to describe a client they believe would benefit from Stretch instead of developing an occupational profile. Overall, survey participants described clients with motor impairments (15/16) that are cognitively intact (2/16). One participant described a client that has quadriplegia due to a diving accident. After the accident, "*she felt hopeless and depressed. [Stretch] could change her entire outlook on life*" (**S6**).

8.3.5 Occupational Therapist Role in Implementing Stretch

During the interview, participants were able to remotely control the Stretch robot, that was in the researcher's home, using the same teleoperation interface our lead user used during our home deployment. We asked participants how they would change to interface to better accommodate the clients they developed occupational profiles for. Some changes included moving button pads, adding/removing camera views, adding a feature for recording and replaying movements, and changing button icons to text. These were all changes that we were able to make through the interface's customization feature. The participants made some recommendations for further improvements based on the current limitations of the interface: changing colors for more visual contrast, adding the ability to enlarge elements, an AR feature that shows the robot's state from a third person point-of-view, and adding more autonomy. All participants spoke favorably about the ability to customize the interface and can see themselves customizing it for their clients. One participant specifically noted it would be helpful to get training on how to use the interface and customize it for their clients: "*I think it would be really cool to get training [from the company] and then help the client customize it, and then, if you have any questions, you could reach out to [to the company]* (**I10**)." The participants felt that they would have the most impact in teaching the client to use the robot and setting up/customizing the robot to enable their client to achieve their goals.

Chapter 9

CONCLUSION & DISCUSSION

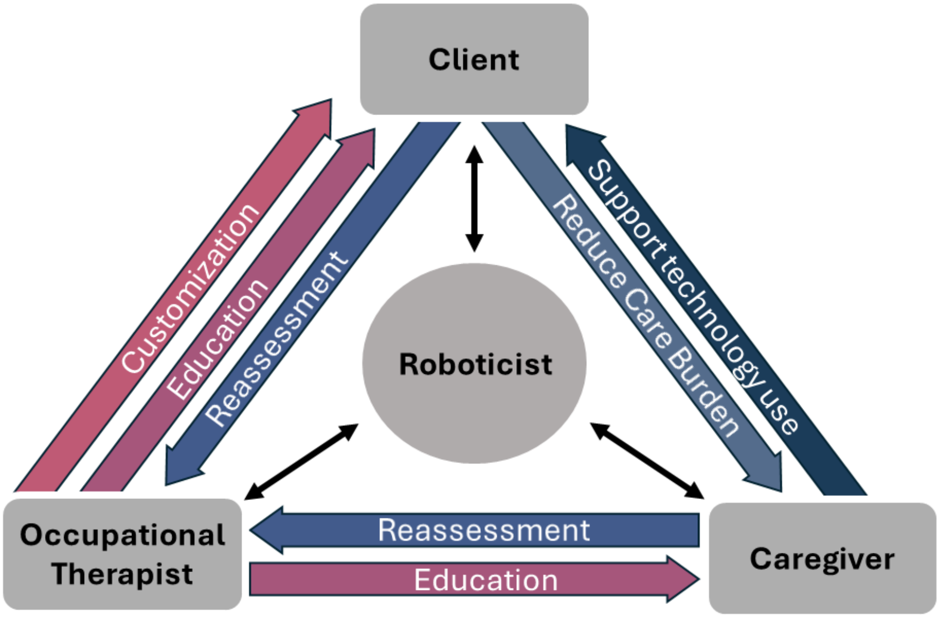


Figure 9.1: A model for stakeholder involvement during implementation of assistive robots

9.1 *Recommendations for Developing Assistive Robots*

Our work confirms the utility and potential impact of assistive robots for individuals with motor impairments. However, ensuring the successful implementation of assistive robots requires careful consideration of several factors and areas for improvement. We have identified numerous barriers and challenges associated with the implementation of ATs, many of which extend to assistive robots. Additionally, while ATs are typically designed to perform specific tasks, assistive robots possess broader capabilities, making them more complex.

In light of these challenges, we propose recommendations that address both the common challenges faced by OTs with ATs and the unique complexities presented by assistive robots. Specifically, our recommendations are informed by a model that identifies three key stakeholders: the client, OT, and caregiver (Fig. 9.1). In prior work, roboticists have worked with end-users to better inform the design of their assistive robot system [15, 30, 29, 61], with caregivers to develop systems that will help with their caregiving duties [16, 60, 4], and OTs to inform the design of physically assistive robots [54, 6]. Our model, recommends roboticists to engage with all stakeholders as they are all crucial for the development and implementation of assistive robots for end-users. By considering the needs and perspectives of each stakeholder group, our design recommendations aim to enhance the usability and effectiveness of assistive robots in real-world settings.

9.1.1 Adaptation to Client's Needs and Functional Abilities

When an OT works with a client, they assess the client's abilities and goals, and develop an intervention plan to help the client achieve those goals. A tool may be selected to assist the client in reaching their desired goals. Our work shows that assistive robots can be effective tools for users. However, for successful implementation, robots must be customizable so that OTs can tailor the robot's capabilities or control interface to match the client's unique needs and abilities. **This value of customization was confirmed by participants across all user studies**. The end-users with motor impairments who participated in our in-lab and in-home studies customized the interface to meet their needs and preferences. The OTs we interviewed customized the interface to align with the needs and abilities of the clients described in the occupational profiles they developed. Additionally, the OTs that participated in the interviews and surveys emphasized the importance of ATs being able to adapt to clients' changing abilities. ATs that cannot adjust to users' abilities can pose challenges during implementation and may eventually lead to device abandonment.

Successful customization can benefit all stakeholders during robot implementation. The OT collaborates with the client to customize the robot and educates them on its use. If the client's abilities change, or they encounter difficulties while using the robot, the OT will reassess and make any necessary adjustments. Successful implementation also includes caregiver involvement, as they will be assisting the client more frequently with setup and maintenance in their environment. The OT educates caregivers on how to set up and maintain the robot in the home environment, and provides re-education if changes are made. Proper customization by the OT and support from the caregiver contribute to effective use and can reduce caregiver burden.

9.1.2 User Experience

Assistive robots must be easy to learn, use, set up, and maintain. OTs need to be able to learn and use the device to adapt it to their clients' needs, develop interventions to help clients achieve their goals, educate clients on using the device, and instruct caregivers on setup and maintenance. Abandonment is a long-standing issue with ATs. Developing a robot that is easy-to-use will reduce the risk of abandonment. Additionally, the robot must be easy to set up and maintain to ensure caregiver support and prevent burden. Assistive robots must provide a seamless user experience for OTs, their clients, and the caregivers to achieve successful implementation

9.1.3 Affordability & Reliability

OTs have identified cost as one of the biggest barriers to prescribing ATs, and this challenge extends to assistive robots, which are significantly more expensive. For example, the Labrador robot is priced at $1,499, with additional monthly fees of either $99 or $149 depending on the model. The Kinova Jaco arm ranges from $35,000 to $50,000, and the Stretch robot costs $25,000. Although the prices of robots have decreased in recent years, they are still not affordable for the average consumer. Some OTs have noted that while cost may not be an issue for certain clients, others may refuse to consider using the device if insurance does not cover it. To ensure access for individuals from all financial backgrounds, these robots must be designed to be more affordable, and efforts should be made to secure insurance coverage.

In addition to purchase costs, maintenance and repair expenses must also be affordable. This is closely tied to reliability. The robot must be reliable and not require frequent repairs or maintenance, as this would burden both the client, who may be unable to use the robot during repairs, and the caregiver, who would have to manage additional workload for maintenance. Assistive robots that are expensive to purchase or maintain will not be prescribed to clients from lower socioeconomic backgrounds, thereby increasing disparities in access to assistive technology. Furthermore, robots that are unreliable and require frequent repairs may either not be prescribed at all or may impose a burden on the client or caregiver, potentially leading to abandonment.

9.1.4 Environment Co-Design

When designing assistive robots, the environment in which the robot will be deployed should be taken into account. In our in-home deployment, the OT not only adapted the robot but designed and built specialized tools that Henry could use with the robot to achieve his goals.

Co-designing the robot with the environment will enhance the robot's ability to perform useful tasks for the user. While many tools the OT developed were tailored to Henry's needs, assistive robot designers can develop tools that will make common household items more accessible to the robot, such as light switch adapters. Furthermore, these robots could have multiple end-effectors that can be easily swapped for different tasks. The OT can work with the client to select the appropriate tools and end-effectors that will best suit their home and allow them to perform their desired tasks, and the caregiver can help support the setup.

9.1.5 Safety & Privacy

Several OTs shared concerns relating to safety and privacy of assistive robots. More specifically, they were concerned with the risks associated with the robot malfunctioning and the data that would be collected from the sensors onboard the robot. Safety mechanisms should be put in place to minimize the likelihood of accidents, and the developers must be cautious when handling user data. This will enable OTs to effectively educate both clients and caregivers on proper usage and safety protocols. By prioritizing safety and privacy considerations and providing adequate support and guidance to OTs, we can enhance the overall user experience and promote the responsible deployment of assistive robots.

9.2 Future Work

9.2.1 Autonomy

This dissertation focused on design and development of a teleoperation interface for an assistive robot platform. While teleoperation is desirable in many contexts, users have expressed interest in adding autonomous submodules that they can trigger to streamline tasks. For example, Henry found it tedious to manually drive Stretch from his room to the kitchen and back due to the long and narrow hallways. As a result, we developed an autonomous navigation feature. The interface displayed a map of the house that Henry could click on to specify the goal and Stretch would autonomously navigate to the destination. Henry was satisfied with this feature and described it as a *"game changer."* Henry has also expressed interest in incorporating autonomous assistance for grasping objects and ArUco-based navigation.

9.2.2 End-User Programming

Henry expressed his desire to automate repetitive tasks such as flipping a light switch. One method to do this without full robot autonomy and allow for custom tasks is end-user programming. We have conducted initial testing with a feature enabling the end-user to record and playback a sequence of joint movements. However, several challenges arise with this method. First, the recordings lack context relative to the object being manipulated. For instance, if the end-user records joint movements for turning off a light switch, the robot must be manually positioned to be inline with the light switch for successful playback. Second, users often encounter difficulty in executing manipulation tasks via teleoperation without errors, such as overshooting, due to the need for precise actions. These errors are captured and reproduced during sequence playback. Future research can investigate methods for post-processing trajectories by identifying errors and consulting the user on whether the movements were intentional. This approach could be coupled with autonomous submodules to enable the user to create custom programs for accomplishing their desired task.

9.2.3 Supporting the Caregiver

We conducted initial explorations on how Stretch could support Jane in her caregiving role and also as an individual. We enabled her personal trainer to teleoperate Stretch during their training sessions, and also developed a mobile prototype of the AccessTeleopKit that Jane used for remote caregiving. While the mobile prototype was successful in helping Jane accomplish her desired use case, future work can explore the needs of a wider population of caregivers and augment the AccessTeleopKit to support their needs.

9.3 Discussion

As the field of robotics advances, it is important to prioritize the needs of the user, ensuring that technological innovations are not only cutting-edge but also deeply impactful and accessible to all. This dissertation focuses on the development of an accessible assistive mobile manipulator platform for individuals with motor limitations, with an emphasis on engaging all stakeholders throughout the process. Beyond functionality, our focus extends to designing technology that can be utilized by individuals with diverse abilities. However, true accessibility extends beyond usability—it necessitates affordability and widespread availability. Therefore, it is essential that the outcomes of our research are not restricted to privileged demographics but are instead accessible to individuals across all socioeconomic backgrounds, empowering universal access to assistive robotics.

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Appendix A

DEMOGRAPHIC INFORMATION OF OCCUPATIONAL THERAPISTS INTERVIEWED AND SURVEYED

ID	Age	Gender	Years of Experience	Specialization	Experience with Assistive Robots?
I1	30	Female	3.5	Acute care/Physical Rehabilitation	No
I2	36	Female	2	Acute care/Stroke	No
I3	48	Female	25	Aging In Place	Yes
I4	36	Female	3	Neuro Rehabilitation	No
I5	53	Female	30	Neuro Rehabilitation	Yes
I6	37	Female	3.5	Acute Care	No
I7	64	Female	38	Geriatrics	Yes
I8	28	Female	4	Community Practice	No
I9	37	Female	3	End-of-Life Care	No
I10	38	Female	2	Acute Care/Outpatient/Home Health	No
S1	37	Female	15	Aging In Place	No
S2	57	Female	36	Geriatrics	No
S3	37	Female	6	Geriatrics/Orthopedics	No
S4	31	Female	10	Assistive Technology/Home Modifications	No
S5	47	Female	21	Geriatrics	No
S6	56	Female	32	Geriatrics	No
S7	25	Female	2	Inpatient Rehab	Yes
S8	30	Female	6	Stroke & Brain Injury	Yes
S9	50	Female	30	Aging in Place	No
S10	26	Female	2	Acute Care	No
S11	37	Female	12	Geriatrics	No
S12	31	Male	3	Geriatrics	No
S13	42	Female	19	Home Health/Inpatient Rehab	No

S14	31	Female	7	Inpatient Rehab	No
S15	25	Female	1.5	Inpatient Rehab	No
S16	34	Female	10	SCI/General Medicine	Yes

Table A.1: Demographic information of participants in the interview (I) and online survey (S)

Appendix B

SUMMARY OF FINDINGS ON BARRIERS WITH EXISTING ASSISTIVE TECHNOLOGY

Barriers preventing AT prescription	**Cost/Reimbursement** (I1, I2, I3, I7, I8, I9, I10, S1, S2, S3, S5, S8, S9, S10, S12), **Client buy-in** (I4, S2, S6, S7, S11), **Time for implementation** (S2, S15), **AT availability** (S11, S15), **Socioeconomic constraints** (I10, S7, S12), **Clinician knowledge gap** (I1, I3, S6, S14), **Clients' cognitive defecits** (S15), **Clients' tech literacy level** (I5, I7, I8), **Physical environmental constraints** (I8, I10)
Factors for assessing the suitability of an AT	**Cognitive abilities** (I4, I6, I8, I9, I10, S1, S2, S3, S7, S8, S11, S12, S14, S16), **Physical abilities** (I4, I8, I10, S1, S4, S7, S8, S14), **Goals** (I2, S1, S8, S9, S10, S12), **Motivation** (I3, I7, S3, S4, S9, S13, S16), **Family/caregiver support** (I7, I9, S2, S3, S4, S7, S9, S11, S12), **Financial status** (I7, S5, S12), **Technology acceptance** (S4), **Ease of use of device** (S15), **Longevity of deficits** (S16), **Suitability of AT in client's home** (I2, I5, I7), **Ability of device to adapt to client's changing needs** (S16, I9)
Current process for learning to use ATs	**Hands-on testing** (I1, I2, I3, I4, I6, I7, I9, I10, S1, S4, S6, S9, S10, S11, S15), **Learning from colleagues** (I2, S2, S3, S7, S8, S10, S16), **Demos from vendors** (I3, I5, I8, I10, S2, S4, S5, S9), **CEUs** (I2, S3, S7, S12, S13), **Internet searches** (S2), **Social media** (S13), **Instruction manual** (S4), **Sponsored trainings** (S3)
Challenges faced when learning to use ATs	**Access** (I4, S2, S5, S8, S10, S11, S12), **Time** (S2, S6, S15), **Setup** (I8, S1, S10, S11), **Complexity** (I7, I9, S1, S3), **Maintenance** (S10), **Apprehension/intimidation towards new technology** (I6, S6), **Resources for learning to use AT** (I2)

Ideal process for learning new ATs	**Hands-on testing** (I2, I7, I10, S2, S6, S8, S12, S14, S15, S16), **Live demonstration** (I1, I3, I5, I6, I8, I9, S4, S7, S11, S12, S13, S15), **CEUs** (I2, S3, S9, S15), **Training from vendor** (I10, S5, S8), **Loan/trial device** (S9, S10), **Instruction manual with photos** (S1, S2), **Videos** (S7), **Inservice** (S16)
Challenges during AT implementation	**Client education** (S1, S6, S12), **Complexity of device** (I1, S2, S14), **Time needed for implementation** (S4, S15), **Family caregiver/support** (I7, S9, S11), **Client buy-in** (S7, S8), **Caregiver education** (S3), **Change in client's abilities** (S3), **Technology failures** (S13), **Client frustration** (I2, S16)
Reasons for AT abandonment	**Frustration** (I2, I7, S1, S6, S16), **Social stigma** (I1, I9, S1, S10), **Complexity of device** (I10, S2, S5, S13), **Lack of family/caregiver support** (I7, S3, S8, S9), **Access** (S2, S5), **AT not fit for the client** (I3, I5, S4, S10), **Change in client's abilities** (I1, I5, I8, S4, S10), **Lack of desire to use consistently** (I2, I4, S11, S13), **Physical environmental constraints** (I2), **Too difficult to set up** (S8), **Maintenance** (S7)

Table B.1: Summary of the barriers and challenges OTs face, their current and ideal learning process for ATs, how they assess ATs and reasons why ATs are abandoned.

Appendix C

SUMMARY OF FINDINGS ON BARRIERS AND CONCERNS WITH ASSISTIVE ROBOTS

Barriers preventing assistive robot prescription	**Lack of education/knowledge** (I1, I2, S1, S2, S3, S4, S5, S6, S9, S11, S12, S13, S14, S15), **Cost** (I1, I3, I6, S1, S4, S5, S8, S9, S10, S16), **Clients' fear of technology** (S3), **Lack of family/caregiver support** (S9), **Access** (S16)
Concerns with prescribing assistive robots	**Constraints of home** (S1), **Client acceptance** (S1, S6), **Safety** (I2, I3, I5, I10), **Privacy** (I5, I8, I9), **Cost** (I1, I4, I6, S4, S5, S6, S7, S8, S9, S15, S16), **Knowledge translation** (S4), **Clinician knowledge** (I1, S6, S9, S11, S14), **Client understanding** (I3, I7, I10), **Socioeconomic constraints** (S7), **Reliability** (S10), **Usability** (I1, I4, I6, I9, S12), **Ability to tailor device to specific client** (S10), **Feasibility** (S15)
Difference between ATs and assistive robots	**Assistive robots are more complex** (S1, S2, S3, S11, S15), **have more capabilities** (S2, S6, S7, S8), **require more maintenance** (S1), **are more expensive** (S6, S12), **customizable** (S10), and **require different skills for implementing interventions** (S4). On the other hand, some participants believe **assistive robots are not customizable** (S14), **are built to assist with a specific occupation** (S15), or **see no difference between assistive robots and other assistive technologies** (S9)

Expectation of robot's abilities	**Ensure safety** (I5, I8, I10), **reminders** (I6, I9, S3, S4), **fall prevention** (I10, S3), **retrieving items** (S3, S4, S9, S12, S14, S16), **monitor appliances** (I10, S3), **answering phone** (S4), should be **customizable** (S5), **assist with mobility** (I6, S11), **medication management** (I6, S11, S3), **feeding** (I2, I5, S11), **grooming** I1, I2, S11), **opening doors** (S11, S15), **increase independence** (I1, S12, S13), **activities of daily living (ADLs)** (I1, I2, I4, I9, S9, S10, S12), and **instrumental activities of daily living (IADLs)** (I4, S15), **improve quality of life** (S7), **increase performance and satisfaction in desired occupation** (S5)

Table C.1: Summary of the barriers and concerns OTs have with assistive robots and their understanding and expectations of its abilities.

Appendix D

SUMMARY OF OCCUPATIONAL PROFILES OF CLIENTS DEVELOPED BY INTERVIEW PARTICIPANTS

ID	**Medical Condition/Motor Impairments**	**Abilities**	**Level of Assistance**	**Roles**	**Targeted Outcomes**
C1	C3 SCI	Cognition intact; technology user; functional neck mobility	Dependent in all ADLs	Family person; law student	Independence in ADLs; socialization
C2	HD; Depression	Cognition intact; Voluntary movements of UE but with limited coordination	Dependent in majority of ADLs	Family person; working professional	Independence in ADLs
C3	Chronic back pain	Cognition intact; Independent but slow movements	Moderate assistance in ADLs	Family person; Retired	Independence in ADLs
C4	ALS; Aphasia	Cognition intact; can preform grooming tasks with setup assistance	Dependence in majority of ADLs	Father; husband; entrepreneur	Socialization; Agency over level of care
C5	ALS	Cognition intact; technology user; some gross motor dexterity	Dependence in majority of ADLs	Husband; father; working professional; sibling	Independence in ADLs/reduce burden of care
C6	SCI	Cognition intact; Functional mobility in UE	Dependence in some ADLs	Friend; brother; son	Independence in ADLs; live alone; Return to workforce

C7	Low vision; Stroke; Right Hemiparesis	Cognition intact; gross motor movement on left side; technology user	Dependence in majority ADLs	Accountant; Spouse	Increase independence; socialize
C8	Age-related motor impairments	Cognition intact; prep meals; navigate through home; technology user	Independent with most ADLs through home modifications	Grandmother; Friend	Return to prior level of abilities; socialization
C9	No use of bilateral UE; limited mobility; Weakness	Cognition intact; Some gross motor movements	Dependence in majority of ADLs	Musician; Gamer; Son; Mechanic; Brother	Have a good death; Regain independence in ADLs before passing
C10	Stroke; Left hemiparesis; Ataxia	Cognition intact; gross motor movement on right side	Dependence in majority of ADLs	Family person; Dog parent	Independence in ADLs

Table D.1: Summary of occupational profiles developed by interview participants for clients that would benefit from the Stretch robot

Appendix E

INTERVIEW QUESTIONS FOR OCCUPATIONAL THERAPISTS

E.1 General Questions about ATs

- What ATs do you use?
- *(If OT does not use ATs)* Why don't you prescribe AT(s)?
- How often do you currently prescribe assistive technology to your clients? (1 – 5)
- How often would you like to prescribe assistive technology to your clients? (1 – 5)
- *(If OTs want to prescribe ATs more frequently)* What barriers are preventing you from prescribing ATs more frequently?
- *(If OTs want to prescribe ATs less frequently)* Why would you like to prescribe ATs less frequently?
- What are the key factors you consider when assessing the suitability of an AT for a specific client?
- How does the frequency of your meetings with clients impact the effectiveness of AT implementation?
- How do you educate yourself on existing ATs?
- How have you learned to use ATs you have prescribed to your clients? What do you like about it? What do you want to change?
- What challenges do you face when learning how to use new ATs?
- What is the ideal process you would go through to learn about a new AT?
- Have your clients ever abandoned the AT(s) that you prescribed? Why?
- Do you have any specific concerns about using AT(s)?

E.2 Questions about Assistive Robots

- What is your understanding about robots and how are they different from other ATs?
- Given your current understanding of robots, how likely are you to prescribe them to your clients? (1 – 5)
- Given your understanding of robots, what would you expect a robot to be able to do for your client(s)?

- Do you have any concerns about prescribing robots to your clients?
- What should the price range be for a robot?

E.3 Questions about Labrador Robotics

The participant watches a video on the robot's capabilities.

- Given the robot's abilities do you think it would be useful to any of your clients?
- Do you think your clients would like this kind of robot in their home?
- How likely are you to prescribe this robot to your clients? (1 – 5)

E.4 Questions about Kinova Jaco

The participant watches a video on the robot's capabilities.

- Given the robot's abilities do you think it would be useful to any of your clients?
- Do you think your clients would like this kind of robot in their home?
- How likely are you to prescribe this robot to your clients? (1 – 5)

E.5 Questions about Stretch

The participant watches a video on the robot's capabilities.

- Given the robot's abilities do you think it would be useful to any of your clients?
- Do you think your clients would like this kind of robot in their home?
- How likely are you to prescribe this robot to your clients? (1 – 5)

The participant watches a video of Henry Evans using Stretch in his home and the question above are repeated.

E.6 Questions to Develop an Occupational Profile

- Describe this client's motor impairments
- In what occupations does the client feel successful, and what barriers are affecting their success in desired occupations? (e.g. environment, personal)
- What are the client's daily life roles?
- What factors does the client see as supporting engagement in desired occupations, and what aspects are inhibiting engagement? (e.g. values, body functions, body structures)

- What are the client's priorities and desired targeted outcomes?
- Is there anything else you would like to add to this occupational profile?
- How would you modify the environment/home to make it accessible for both your client and the robot? Are you comfortable creating these modifications?
- Would you want the company to assist you in making modifications for the robot? If yes, how?
- If you needed help or wanted to give feedback about anything related to Stretch, what would you want that process to look like?

E.7 Questions about the AccessTeleopKit

The facilitator guides the participant on how to use the interface for remote controlling Stretch. They are then instructed to use the interface to drive the robot and pick up an object on a table.

- (Before performing task) Is there anything that you do not understand about this interface?
- Could you list 3 adjectives about your impression of this interface?
- (After performing the task) Was there anything that confused you while performing the task, if any?
- How would you change the interface for the client in your occupational profile? This can be changing the layout, new features, etc. (*If it is possible to re-create that interface, the facilitator shows them how to do it.*)
- What did you like or not like about the interface?

E.8 Questions about On-boarding

The facilitator describes the following on-boarding steps: (1) unboxing (2) setting up the robot, (3) receiving instructions, and (4) testing the first feature

- Could you describe what you'd expect for each step? And why? Do you expect a written manual or voice guide? You can be creative and choose any medium.
- From the on-boarding steps mentioned, where do you see OT's role have the most impact? Do you want to be involved in ordering the robot, setting it up for your clients, going to the clients home, etc?
- How much should the client be involved during the on-boarding experience, specifically for Stretch?

E.9 Demographic Questions

- Age
- Sex (Male, Female, Other)
- How many years have you been practicing occupational therapy?
- What area(s) of OT do you specialize in?
- Would you be willing to participate in follow-up studies?

Appendix F

SURVEY QUESTIONS FOR OCCUPATIONAL THERAPISTS

F.1 General Questions about ATs

- What ATs do you use?
- How often do you currently prescribe assistive technology to your clients? Please indicate the rough percentage of your clients to whom you prescribe assistive technology.
- What portion of your clients do you think could benefit from assistive technology (independent of whether you prescribe it)?
- Would you like to prescribe assistive technology to your clients more or less often?
- What barriers are preventing you from prescribing ATs more frequently? (Leave blank if not applicable)
- Why would you like to prescribe ATs less frequently? (Leave blank if not applicable)
- What are the key factors you consider when assessing the suitability of an AT for a specific client?
- How do you educate yourself on existing ATs?
- How have you learned to use ATs you have prescribed to your clients? What do you like about it? What do you want to change?
- What challenges do you face when learning how to use new ATs?
- What is the ideal process you would go through to learn about a new AT?
- What challenges do you face during the implementation of new ATs?
- Have your clients ever abandoned the AT(s) that you prescribed? Why?
- Do you have any other concerns about using AT(s) not mentioned in previous answers?

F.2 Questions about Assistive Robots

- Are you aware of any existing assistive robots? Do you have any experience with them? If yes, please describe the assistive robots you use in your practice.
- How often do you currently prescribe assistive robots to your clients? Please indicate the rough percentage of your clients to whom you prescribe assistive robots.
- What portion of your clients do you think could benefit from assistive robots (independent of whether you prescribe it)?

- Would you like to prescribe assistive robots to your clients more or less often?
- What barriers are preventing you from prescribing assistive robots more frequently?
- Do you have any concerns about prescribing assistive robots to your clients?
- In what ways do you think assistive robots are different from other ATs?
- What would you expect a robot to be able to do for your client(s)?
- What should the price range be for a robot?

F.3 Questions about Labrador Robotics

The participant watches a video on the robot's capabilities.

- What portion of your clients do you think could benefit from the Labrador Robot?
- Please describe clients that would most benefit from the Labrador Robot. In what ways would the robot help?
- Do you have any concerns about prescribing the Labrador Robot to your clients?
- What should the price range be for the Labrador Robot given the robot's abilities?

F.4 Questions about Kinova Jaco

The participant watches a video on the robot's capabilities.

- What portion of your clients do you think could benefit from the Jaco Robot?
- Please describe clients that would most benefit from the Jaco Robot. In what ways would the robot help?
- Do you have any concerns about prescribing the Jaco Robot to your clients?
- What should the price range be for the Jaco Robot given the robot's abilities?

F.5 Questions about Stretch

The participant watches a video on the robot's capabilities.

- What portion of your clients do you think could benefit from the Stretch Robot?
- Please describe clients that would most benefit from the Stretch Robot. In what ways would the robot help?
- Do you have any concerns about prescribing the Stretch Robot to your clients?
- What should the price range be for the Stretch Robot given the robot's abilities?

F.6 OT Case Study of the Stretch Robot

The participant watches a video of Henry Evans using Stretch in his home.

- After seeing Henry's use of the Stretch robot, what portion of your clients do you think could benefit from the Stretch Robot?
- After seeing Henry's use of the Stretch robot, can you think of more ways your clients could benefit from the Stretch Robot?
- After seeing Henry's use of the Stretch robot, do you have any additional concerns about prescribing the Stretch Robot to your clients?

F.7 Client that May Benefit from Having Stretch in Their Home

- Please describe one specific client that you think would benefit from having Stretch in their home. This can be a hypothetical client or a client you have seen before.
- How would you modify the environment/home to make it accessible for both your client and the robot? Are you comfortable creating these modifications?
- Would you want the company to assist you in making modifications for the robot? If yes, how?
- If you needed help or wanted to give feedback about anything related to Stretch, what would you want that process to look like?

F.8 Demographic Questions

- Age
- Sex (Male, Female, Other)
- What area(s) of occupational therapy do you specialize in?
- How many years have you been practicing occupational therapy?
- Please describe all adult client populations with motor impairments that you have experience working with with.
- Would you be willing to participate in follow-up studies?