DEVELOPMENT AND ASSESSMENT OF ADVANCED ASSISTIVE ROBOTIC MANIPULATORS USER INTERFACES

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Assistive Robotic Manipulators (ARM) have shown improvement in self-care and increased independence among people with severe upper extremity disabilities. With an ARM mounted on the side of an electric powered wheelchair, an ARM may provide manipulation assistance, such as picking up object, eating, drinking, dressing, reaching out, or opening doors. However, existing assessment tools are inconsistent between studies, time consuming, and unclear in clinical effectiveness. Therefore, in this research, we have developed an ADL task board evaluation tool that provides standardized, efficient, and reliable assessment of ARM performance. Among powered wheelchair users and able-bodied controls using two commercial ARM user interfaces – joystick and keypad, we found that there were statistical differences between both user interface performances, but no statistical difference was found in the cognitive loading. The ADL task board demonstrated highly correlated performance with an existing functional assessment tool, Wolf Motor Function Test. Through this study, we have also identified barriers and limits in current commercial user interfaces and developed smartphone and assistive sliding-autonomy user interfaces that yields improved performance. Testing results from our smartphone manual interface revealed statistically faster performance. The assistive sliding-autonomy interface helped seamlessly correct the error seen with autonomous functions.

The ADL task performance evaluation tool may help clinicians and researchers better access ARM user interfaces and evaluated the efficacy of customized user interfaces to improve performance. The smartphone manual interface demonstrated improved performance and the

sliding-autonomy framework showed enhanced success with tasks without recalculating path planning and recognition.

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PREFACE

I would first and foremost like to thank my Creator, who created me and formed what I am today. I would also like to thank my wife, her love and support made this work happen. Although she knows nothing about programming or mechanical design, her trust in my capability and that who began the work will carry it on to completion until the day gave me strength and enlightened me. I would like to thank my parents, who always support and encourage me. Without them, I would not be able to overcome the difficulties in my academic journey.

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1.0 INTRODUCTION

1.1 TARGET POPULATION

Assistance needs for daily manipulation are increasing. According to a report [1], in the United States, about 19.9 million people age of 15 years and older have difficulties with physical tasks related with the upper extremity functioning, including lifting, grasping, pushing/pulling, reaching, dressing and eating. Among people with upper extremity disabilities, about 17.2 million people have difficulty lifting a 10-pound object like a bag of groceries, and 6.7 million people have difficulty grasping objects like a glass or pencil. Among the 17.2 million people, about 8.1 million were unable to lift a 10-pound object. About 893,000 people were unable to grasp objects. This population includes people with muscular dystrophy (MD), spinal cord injury (SCI), spinal muscular atrophy (SMA), multiple sclerosis (MS), amyotrophic lateral sclerosis, cerebral palsy (CP), rheumatoid arthritis (RA), postpolio syndrome, locked-in syndrome, and other severe motor paralysis [2]. In the population 65 and older, about 9.2 million reported difficulty with lifting or grasping. In addition, the elderly population will be expected to increase from 35 million in 2000 to 87 million in 2050. Among older adults, the estimation of older adults with moderate to severe disabilities has also increased from 10 million in 2000 to 24.6 million people in 2040 [3]. These statistics revealed the increasing need for personal care attendants for people with disabilities and older adults.

1.2 CARE GAP

However, assistance from caregivers is decreasing. A severe shortage of both paid and family-provided personal care attendants has been reported [4], [5]. In the paid care attendants, incompatible income to other jobs in conjunction with higher physical and emotional demand are two of the main causes. These causes discourage care attendants to leave to find higher income or less stressful jobs. These causes result in high turnover and vacancy rates, i.e. people with disability receive less time with assistance. Fortunately, this vacancy was filled by family members in the past. However, personal care by family members is dropping. The ratio of the number of females between 25 and 54 and each person 65 and older was 1.74 in 2000 but is expected to drop to 0.92 by 2030 [4]. This means that less people in the family will be available to provide assistance due to a full-time job. If these statistical estimations are correct, by 2030-2040, there will be 11.9 million people (34.45% among people with difficulties in tasks relating to upper extremity functioning) facing a situation that families are short handed in time to care for older adults by themselves and also find that the paid assistance has less staff available to fill this “care gap” (Figure 1). The growing needs for daily manipulation in conjunction with reducing personal care assistance enlarges the “care gap” that will lead to a compromised quality and quantity in personal care and result in reduced quality of life (QOL) for people with disabilities, older adults, and their families.

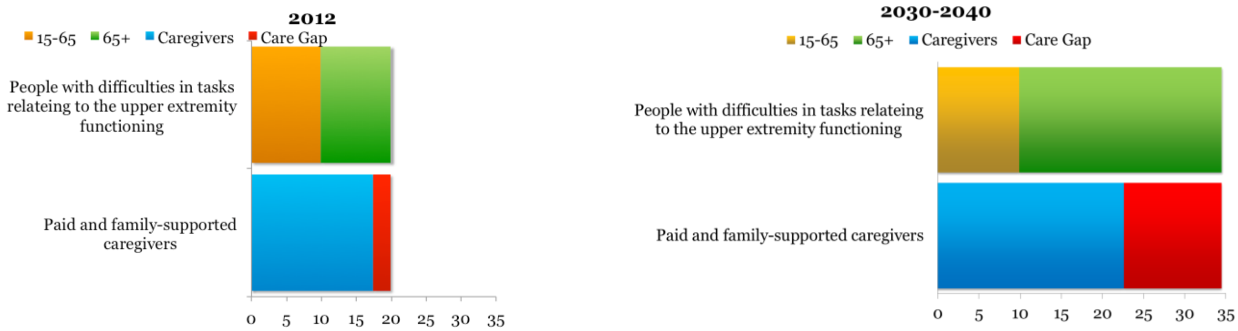

Figure 1. The 2012 (left) and the estimation at 2030-2040 (right) of the population with difficulties in tasks relating to the upper extremity functioning and the paid and family-supported caregivers (Unit: Million People).

1.3 ASSISTIVE ROBOTIC MANIPULATORS

To alleviate the enlarging “care gap,” the solution of increasing caregiving workforce is a slow process because it is time-consuming to change the factors that affect long-term care assistants, such as the social-cultural view, career training, and long-term care policy including insurance reimbursement, labor, welfare, educational support, and immigration [5]. As an alternative solution to fill this “care gap”, assistive robotic manipulators (ARMs) have been developed and provide enhanced assistance to people with impairments in completing activities of daily living (ADL) while a care attendant is not on site [6]. A robotic assistive manipulator can be mounted either on a wheelchair or mobile base. It was estimated that about 150,000 people (0.06%) in the United States can benefit from using ARMs [2]. In addition, among growing older people with the degenerative symptoms, the needs for assistance in object manipulation will also increase [7]. Other than just filling the “care gap” described previously, ARMs also demonstrated enhanced independence in the ADL tasks. Studies [8], [9] have shown that ARM users could independently perform home and vocational tasks.

ARMs are not a newly developed technology, the research and development of ARMs, including wheelchair- and desktop-mounted robotic manipulators, can be traced back to the 1960s. Over the past fifty years, nearly a dozen assistive robotic manipulators have been developed and evaluated for their performance in usability and functionality. Different user interfaces have been designed for each of these assistive robotic manipulators to improve the performance of accomplishing functional activities of daily life (ADLs). The involvement of user experiences and feedback from the target population has kept the design and development progressing. In addition, with the benefit of increasing computational power, more research groups have developed automation and artificial intelligence for object recognition and path planning so that people with disabilities may perform ADLs and vocational tasks more independently and efficiently. However, despite of these attempts, there are only few commercialized assistive robotic manipulators currently available on the market.

A literature review [10] in 1994 summarized the results of nine surveys that identify the task priorities from the robotic devices. Another survey [11] in 2002 added more studies for new commercial ARMs. A literature review article [12] compared 19 commercial and developing ARM with five criteria: interaction safety, shock robustness, adaptability, energy, and position control. These robotic manipulators were compared through their functionalities and specifications. However, their costs, user interfaces, and clinical efficacy to help people with disabilities were not taken into consideration. Thus, there was no literature review that discusses the clinical effectiveness with the most recent commercialized ARMs. How well can these ARM perform? How do clinicians evaluate them? How was their performance improved? Can their results be systematically integrated? Therefore, we conduct a literature review study to answer these questions to determine the ARM's current performance and barriers.

Furthermore, although studies with integrated autonomy through object recognition demonstrated reduced the completion time in specific tasks, the success rate was compromised [7] and participants felt isolated from the system [13].

1.4 CURRENT COMMERCIAL ARMS AND USER INTERFACES

Figure 2. Two commercialized wheelchair-mounted robotic manipulators: JACO manipulator (left) and Manus ARM (right).

Two commercialized assistive robotic manipulators (iARM and JACO manipulator, shown in Figure 2) have more than 6 DOF and minimized fold-in position. The iARM has a two-finger gripper manufactured by Exact Dynamics. It can be controlled by keypad, joystick, or single-button switches through a CAN bus [14], [15]. Alternatively, the JACO manipulator has a threefingered hand manufactured by Kinova Technology. The hand can grasp objects using either two or three fingers. It can be controlled by its own 3-DOF joystick [16], [17].

1.5 RESEARCH GOALS

The goal of this research work was to answer the two key questions related to the ARM user interfaces: 1) how well current user interfaces perform? And 2) can we make better user interfaces? Chapter 2 introduces the conducted literature review in clinical evaluation of performance and functional assessment used to inspect user interfaces using International Classification of Functioning, Disability, and Health (ICF) codes, World Health Organization (WHO). Chapter 3 describes a standardized ADL task board system as well as adapted Wolf Motor Function Test to measure how well the commercial user interfaces perform. An ADL task board system was built and software were developed to automatically record the ARM performance and trajectories. In Chapter 4, we conducted a study to evaluate the commercial user interfaces. Task completion time, roughness, pause time, cognitive loading, and throughput were determined to characterize the effectiveness of ARM user interfaces. Additionally, this chapter describes the barriers for the first-time users and establishes norm data among able-bodied control participants and powered wheelchair users. Further, this chapter also determines the reliability, validity, and responsiveness of applying this measurement tool for clinical assessment. Chapter 5 describes the development of the advanced ARM user interfaces that show improvement in both current manual and autonomous use interfaces. The outcome of this work will provide clinicians and researchers a reliable and valid tool to assess ARM's user interface performance. A viable and improved ARM framework will be introduced for ARM developers to seamlessly include the autonomous function in the task performance.

2.0 REVIEW OF ARM USER INTERFACES PERFORMANCE EVALUATIONS

To answer the first question of how well current user interfaces perform, we first conducted a literature review to explore existing function assessment and performance evaluation studies on customized and commercial user interfaces. There was no literature review in functional and performance effectiveness since 2002. Therefore, recent commercial ARMs were not included in the previous review articles [11], [18]. We selected and reviewed studies that involved people with manipulation needs, including surveys, short-term testing, or long-term studies. The study testing results were categorized using ICF codes in order to 1) demonstrates the perspectives with functional assistance and health enhancement from the ARM usage; and 2) identify categories that have not been explored.

In this chapter, we will first list the studies reviewed with their user interfaces and participants. The performance and functional assessments used in the reviewed studies are summarized. In the last section, the study results are concluded using ICF codes.

2.1 ARM USER INTERFACES

In this section, we will introduce the standard commercial ARM user interfaces and user interfaces under development from previous studies that involve participants with manipulation needs.

Figure 3. The iARM 16 keys of the Medium & Large keypad are provided with numbers and letters (0-9 and A-F) and the user interface of the Android application (iMove).

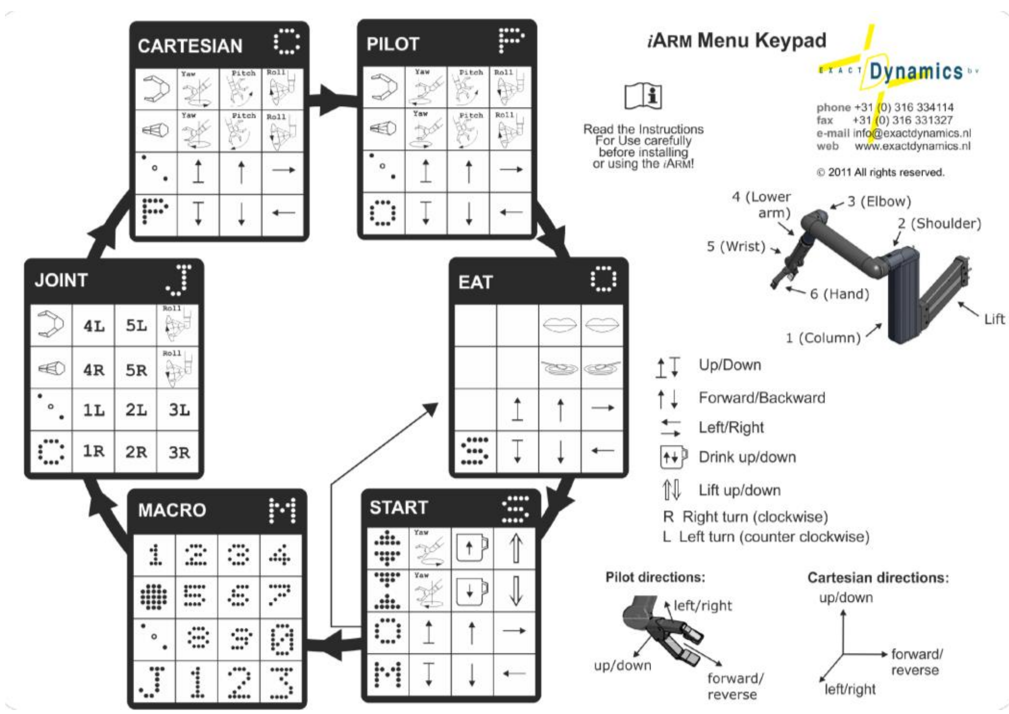

Figure 4. The menu structure of all functions of the various keys on the keypad is shown (source: iARM user manual).

As aforementioned, there are two ARMs that can be mounted on the wheelchairs commercially. The iARM's user interface is a 4x4 keypad (as shown in Figure 3), on which labeled with number 0-9 and character A-F. Each key function depends on the mode menu. For example, in the Cartesian mode menu, pressing the key "C" will move the hand to the left, but in Joint mode menu, the same key will rotate the elbow (axis3) to the right. Once the iARM starts moving, it will not stop until the stop key "1" is pressed or when reaching the limit of the workspace. Pressing multiple times of the same key will accelerate or decelerate the ARM motion. For example, if the user had pressed key "C" twice, pressing key "C" again will increase the speed moving left and pressing key "D" more than twice will move the ARM to the right. Pressing key "A" will switch modes following the order: Start->Macro->Joint->Cartesian->Pilot->Eat (Figure 4). There was an Android smartphone application on Google Play (http://play.google.com/store/apps/details?id=com.ed.iMove&hl=en), which connects, to the iARM through Bluetooth. In this application, each key is labeled with the pictures shown in the menu structure (Figure 3).

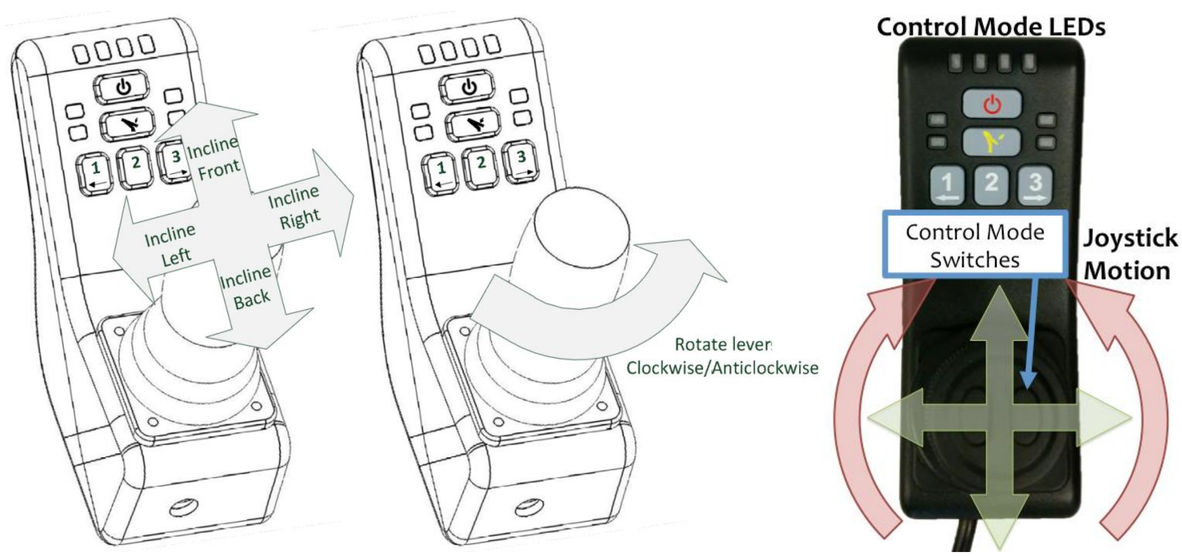

Figure 5. JACO ARM user interface

The JACO ARM's original user interface is a 3-axis joystick (Figure 5), which consists a joystick with rotational knob and two mode switch buttons. The joystick correlates with different ARM motions depending on the control mode. There are three control modes: translation, wrist rotation, and finger modes. For example, twisting the knob clockwise will move the ARM upwards in translation mode, but rotate the wrist clockwise in the wrist rotation mode. Different from the iARM, the speed control is proportional, similar to power wheelchair control. Once the joystick is released, the ARM will stop.

The reviewed studies are listed in Table 1. As we can see, most studies only included one single user interface or one single ARM. The only study [9] in 1990, which compares between the user interfaces and AMRs, is outdated. The ARMs used in that study were discontinued already. There was no previous study found that compares current commercial user interfaces except the green colored row, which is one of the studies in Chapter 3, 4, and 5.

Table 1. List of the selected studies with tested robotic manipulator, user interfaces and participants.

Study	User Interface	Robot	Participants
Corker, 1979 [18]	**Joystick** **Tongue-actuated switches**	**Golden Arm**	**n=3 (SCI, Guillain Barre, and MS)**
Hammel et al., 1989 [8]	**Voice control**	**Desktop vocational assistant robotic workstation**	**n=24 (SCI)**
Bach, Zeelenberg, & Winter, 1990 [19]	**12-key keypad for joint control** **2 joysticks with scanning command selection**	**Industrial robot** **Cobra RS2** **Microbot 453-H**	**n=6 (DMD)**
Buhler, 1994; Bühler, Hoelper, Hoyer, & Humann, 1995 [20], [21]	**Standard 4x4 keypad**	**Manus ARM**	**1st test: n=13** **MD: n=2** **Spastic tetraplegia: n=4** **Polyomyelitis: n=1** **Intracranial pressure (ICP): n=5** **Spina bifida: n=1**

Table 1 (continued)

			2nd test: n=2 **(MD & Spastic tetraplegia)**
Shoupu Chen, Rahman, & Foulds, 1998 [22]	**Head-operate user interface**	**PerForce1 made by the Cybernet Systems Corporation**	**n=6 (able-bodied)**
Schuyler & Mahoney, 2000 [23]	**GUI interface with 3 modes: Joint, Program, and Procedure** **Computer access: intellikeys, WiViK scanning**	**Desktop-mounted UMI-RTX**	**n=9 (CP)**
Romer, Stuyt, & Peters, 2005; Römer, Stuyt, Peters, & Woerden, 2004 [24], [25]	**Standard 4x4 keypad** **Wheelchair joystick**	**Manus ARM**	**n=13 (experienced)** **n=21 (non-experienced)**
B. Driessen et al., 2005 [15]	**Wheelchair joystick with 3 modes: Cartesian, pilot, and joint modes and collaborative with camera on fingertip**	**Manus ARM**	**n=4 (experienced)**
Tijsma, Liefhebber, & Herder, 2005 [26]	**Costumed GUI**	**Manus ARM**	**n=4 (powered wheelchair users with weak upper limb strength)**
Romer et al., 2005 [25]	**Wheelchair joystick with 3 modes: Cartesian, pilot, and joint modes and collaborative with camera on fingertip**	**Manus ARM**	**n=4 (experienced)**
Laffont et al., 2009 [2]	**GUI with panoramic camera** **Computer access: trackball, simple mouse, and head tracking**	**Manus ARM**	**n=20** **MD: n=5** **traumatic tetraplegia: n=13** **Guillain- Barré syndrome: n-2**
Haigh & Yanco, 2002; K. M. Tsui et al., 2011; K. Tsui & Yanco, 2007 [7], [11], [27]	**Touchscreen to select object** **Computer access: touch screen, touchscreen with key-guard, single switch scanning, and head pointer**	**Manus ARM**	**n=12** **traumatic brain injury: n=5** **CP: n=6** **Spina Bifida: n=1**
Routhier & Archambault, 2010 [28]	**Standard 3-axis joystick**	**JACO manipulator**	**n=22** **SCI: n=11** **MD: n=5** **Others: n=7**
Maheu et al., 2011 [16]	**Standard 3-axis joystick**	**JACO manipulator**	**n=31**
Kim, Wang, & Behal, 2012 [29]	**Manual and autonomous mode**	**UCF-MANUS**	**n=10 (SCI)**
Cooper et al., 2012 [30]	**Manual mode using touch screen** **Tele-operation mode using Phantom Omni haptic joystick**	**PerMMA**	**n=15 (power wheelchairs users with upper and lower extremity impairments)**
Chung et al., 2014 [31]	**Keyboard** **Standard 3-axis joystick**	**iARM** **JACO manipulator**	**n=10 (power wheelchair users)**

2.2 PERFORMANCE MEASUREMENTS OF COMMERCIALIZED AND DEVELOPING ARM USER INTERFACES

In this section, we will review the outcome measurements used in the previous studies. Basically, the ARMs were evaluated by performing different tasks, either related to ADL directly or indirectly. We categorized the assessments in studies based on their outcome measurements and task complexity, shown in Table 2. The outcome measurements were categorized by the capability in evaluating performance, the vertical dimension in Table 2. For example, studies using the success rate as outcome measure can only show the functional ability in completing specified task, but it is not able to demonstrate how long it will take. On the other end, using Fitts' parameters and trajectory analysis not only tell how fast the task was done, but also where the difficult part of the task is. The horizontal dimension is the relativity to ADL tasks, from non-related to sequential task. For example, the block and box test is commonly used to evaluate arm performance, but the 1" cube size is less related to any ADLs. On the other end, the meal preparation or eating is apparently an ADL, which requires serious actions to perform in order to finish the whole task. Tasks in between include single action task, such as pushing buttons, pick and place, or put blocks; and multiple actions including drinking, retrieving tissues. The less ADL related task using without timing, the lower left corner, does not exist in the reviewed articles because there is no clinical meaning to use these kinds of measures. The single action task can be measured through the Fitts' parameters because they have clearly defined start and end locations. The more complicated sequential tasks are difficult to be measured in Fitts' parameters due to large individual variation in the strategies, habits, and recovery from errors.

The highlighted are the tasks used in the study described in Chapter 3, 4, and 5, which has never been evaluated before. The detail of the studies is summarized as follows.

Table 2. Assessments in studies based on their outcome measurements and task complexity

Fitts parameter Trajectory analysis	Peg-in-hole © [18] Touch two targets [22]	Performance	Pushing Buttons [32] Turning Knob/Key [31], [32] Opening door [32]		
Number of clicks/mode switches Number of commands		Evaluation	Pick and place [18], [20], [25], [26], [29], [33], [34] Pick up pens [24], [26] Put blocks [24], [26]	Wolf Motor Function Test © [31] Drinking [31], [34]	
Task completion time	Block & Box © [23] Minnesota Test © [23]		Pick and place [31]	Jebson Hand Test © [23] Retrieve a tissue [34]	Meal preparation [34] Eating [34] Finish a meal [9]
	Less ADL Related				Highly ADL Related
Success rate Easiness Perceived mental loading Average daily usage Assistance time Interviews		Functional Assessment	Pick and place [2], [11], [16], [20], [21], [24], [25], [28] Lift up object from the floor [20], [21] Shaving [8], [20], [21] Push button [16], [28]	Drawing lines [22] Drinking [22], [24], [25] Feeding Pets [24], [25] Take a tissue [16], [28] Open door/drawer [20], [21] Pickup hidden object [15] Page turning [22] Wolf Motor Function Test © [31]	Meal preparation [8] Operating devices (VCR) [24], [25] Pour water [16], [28] Wash face/Teeth [8], [24], [25] Eating [8], [9], [20], [21], [24], [25]
			Single action	Multiple actions	Sequential tasks

The University of California conducted a long-term study with three participants with SCI, Guillain Barre, and MS (two males and one female, age: 47-54 year) for months. The control interface of the Rancho Los Amigos (Golden Arm) Manipulator for two participants was a proportional joystick that sequentially drove each joint motor. The other participants with SCI used tongue-actuated switches. Performance was evaluated using a modified peg-in-hole test.

The test was to put different shapes of blocks into an associated hole on the lap tray with constant tolerance and trajectory distance. A Fitts' Index of Difficulty (ID) measure was utilized for standardization.

$$ID = \log_2\left(\frac{2 \times \text{Distance}}{\text{Tolerance}}\right)$$

The excise task was to bring a stand and a book on the lap tray where it was reachable with a mouth-stick. The completion time of the peg-in-hole test was recorded every hour to demonstrate the learning effect. During the long-term study, an integrated circuit system recorded the frequency of daily usage to reflect the objective view of the usefulness of the manipulator in ADL. The problems were also investigated periodically with a Critical Incident Technique interview.

Participants were able to complete the peg-in-hole test within 4 minutes after using the manipulator for 13 hours. The number of control commands to complete a task was highly correlated with the total task time (Pearson's r = 0.91). Participants performed statistically more horizontal and vertical movements than the rotational movements [18].

Voice control can be useful for individuals who have difficulty using joysticks or keypads. A study of 24 high-level quadriplegics (C1-C5, age: 20-73 year) from the Palo Alto Veterans Affairs Spinal Cord Injury Center evaluated a desktop vocational assistant robotic workstation. Participants were asked to prepare a meal, feed themselves, wash their face, shave, and brush their teeth using a trained voice recognition interface. Tasks were rated a three-point scale. Measurements of performance were recorded with in-house designed pre- and post-questionnaires, interviews, and observer assessments during training and evaluation. Task completion time is recorded during every task.

1. Prepare soup and feed self: 564±1.89 seconds, range 420-780 seconds with 78% reported satisfied and 22% neutral.
2. Brush teeth and rinse: 325±2.33 seconds, range 114-540 seconds with 95% reported satisfied and 5% neutral.
3. Shave face: 622±4.98 seconds, range 271-840 seconds with 62% reported satisfied and 38% neutral.
4. Wash and dry face: 480±1.73 seconds, range 420-600 seconds with 73% reported satisfied, 20% neutral, 7% dissatisfied.

The comparison between pre- and post-questionnaire showed the shift of acceptance from undecided to accepted [8].

A long-term study of six participants with Duchenne muscular dystrophy (DMD) referred from University Hospital (age: 19-28 years, mean age: 24 years old) were conducted by the University of Medicine and Dentistry of New Jersey. The participants were all wheelchair users without functional movement of the shoulder and elbow but with finger excursion for pressing push buttons (three used ventilators). Two types of industrial robotic manipulators, the Cobra RS2 manipulator (Cobra, Darmstadt, West Germany) and the Microbot 453-H manipulator (Movemaster, Mountain View, CA), were mounted on a stand fixed to the lap tray. Two kinds of user interfaces modified from the industrial control panel were evaluated: keypad and joystick. The keypad consisted of 12 touch-sensitive buttons on a circuit board (4"x5") to control the motors, geared to shoulder, elbow, wrist and terminal device functions. The joystick user interface consisted of two joysticks and two toggle switches. One joystick and two toggle switches were designed for selecting commands using scanning mode, and the other joystick was used to activate the robotic manipulator. The participants used the ARM for 1.5-6 years (3 years on average). The measurement includes the time of daily usage (5-12hr/day, 8.6hr/day on average), eating time (1-2hr using keypad, 1.5-2.5hr using a joystick with scanning selection, 1-2hr with attendant assisted), and average reduced caregiving time (2-4hr/day, 3hr/day on average). Participants were also interviewed about frequently used ADL tasks (Table 3). The three most important tasks of the ARM usage were assistance with eating, manipulation of remote and environmental control devices, and recreational activities. The capability to scratch oneself was also found to be important. Participants' family members noticed improved independence [19].

A study conducted by the Forschungsinstitut Technologie-Behindertenhilfe, Germany was to explore the capability of users with different disabilities to operate the Manus ARM after a short training period. The standard 4x4 keypad from Manus ARM was used for ARM operation. Participants with different disabilities were recruited to perform simple test tasks of driving to a work position and building a tower of three wooden pieces. Five participants (age: 20-40year) were unable to finish this task within the requested time. Satisfactory results with Cartesian mode were reported (good: n=3, medium: n=4, bad: n=6). A negative response in switching menus with the standard keypad led to refusal or rejection in most participants. Two of the most skilled participants were evaluated for ADL tasks with their own choices of typical tasks: taking care of oneself (e.g. shaving); eating, drinking and pouring out the liquid; opening doors and drawers; grabbing and handling objects; retrieving papers out of a file; and lifting up objects from the floor/ground. One participant with MD did finish all these tasks properly and quickly without major problems, while the other with spastic tetraplegia requested to operate the robot at a workstation. Although simplified keypad design was discussed in the study, no clinical result was reported with it [20], [21].

A study was conducted to evaluate a head-operated user interface with force feedback to control a PerForce1 made by the Cybernet Systems Corporation. Six able-bodied (age: 20-40 year) participants were evaluated in performing a Fitts' movement task. Three tasks were used to evaluate the user's performance. In the first task, participants were asked to touch two targets on a board in front with the head-stick or end-effector on the robotic arm for six trials. The completion time and Fitts' Index of Difficulty (ID) was recorded. The ID was calculated as

$$ID = \log_2\left(\frac{2 \times \text{Distance between Targets}}{\text{Width of Target}}\right)$$

The second task was a page-turning task in which the participant continuously turned five pages of a large book with either the head-stick or the robotic manipulator. The task completion time was recorded. The third task was to draw two diagonal straight lines by following an X mark on the paper. Linear error was used to determine the accuracy in control. The head-stick with force feedback showed statistically lower task completion time than the head-stick interface without force feedback [33].

An exploratory study was conducted by duPont Hospital for Children, Wilmington, with the use of standard occupational therapy (OT) assessment tests to measure the effective manipulation performance of individuals with disabilities using a desktop-mounted robotic manipulator (UMI-RTX). Nine participants with severe physical manipulation impairments (CP) were identified through local rehabilitation centers. Three modes of user interfaces were tested: joint, program, and procedure mode. The appropriate computer input method was selected by preliminary evaluation (6 used intellikeys, 1 used WiViK scanning, and 2 used both). Three functional assessment measurements were used: Jebsen Hand Test, Block and Box Test (BBT), and Minnesota Rate of Manipulation Test (MRMT). In all the three functional assessments, the results showed that human–robot performance is significantly slower than test results by people with stroke or other disabilities in comparison with other studies. However, participants were not able to complete any of the tests if there was no ARM used [23].

A study by the Dutch Institute for Rehabilitation Research (iRV) compared 13 long-term Manus ARM users with more than four years experience with 21 non-ARM users who have similar levels of impairments. The user interface used was either the standard 4x4 keypad or wheelchair joystick. Participation in ADL tasks was observed for one week every three months for 12 months and the average daily usage and assistance time was reported. Results showed that one participant applied the ARM for more than 4hr/day, four participants for 2 to 2.5hr/day, and eight users for less or equal than 2hr/day, range from 0.6-3.7hr/day. It showed that the ARM users perform 40% more ADL tasks than the other group. The Manus ARM was used average 2hr/day (0.7-1.8 hours) [24], [25].

A vision-based interface with autonomous planning transfers the loading in positioning and fine adjustment to the computer. A study by TNO Science & Industry, The Netherlands, evaluated four experienced Manus users with the pre- and post-test in retrieving a colored cup located at a location not seen by the users. The wheelchair joystick was implemented with three control modes: Cartesian mode, pilot mode, and joint mode. A camera was mounted on the fingertip to provide visual feedback within a graphical user interface displayed on a 7-inch widescreen TFT display. A visual servoing function was developed for guiding the ARM toward the target cup. Rates of success and difficulties were reported. Participants reported the difficulties in pilot mode and operating the ARM through the camera's view. All participants were able to finish the task with no difficulty using the visual servoing function [15].

Another study using the same graphical user interface was conducted by TNO and Delft University to evaluate Manus ARM with four powered wheelchair users (1 female) with weak upper limb strength. The Manus ARM was mounted on a stand-alone support beside the wheelchair user with adjustment of arm speed and switching method by user's choice. Three tasks were used to evaluate performance: 1) to stack two cups on the table, then pick up a pen and insert into the piled cups using Cartesian, pilot, and collaborative modes; 2) to move two blocks into a box with the normal and adjusted center of rotation modes; 3) to pick up two pens located out of the user's sight with pilot and collaborative modes. The measurements included the number of mode switches, task time, Rating Scale of Mental Effort (RSME), and interviews of suggestions on the new interface. Data were analyzed using 2x2 (method of mode switching: original and new; control modes: Cartesian and pilot) analysis of variance (ANOVA). Due to limited trials for training and a small sample size, the results showed no statistical difference among these four conditions [26].

A multi-center study was conducted to evaluate the efficacy of a graphic user interface with a panoramic camera to identify out-of-sight objects to be retrieved by Manus ARM automatically. There were 20 participants recruited (7 females; mean age: 44 year, range: 26-67 year) from 4 physical medicine and rehabilitation units of French hospitals (Coubert, Reims, Berck sur Mer, Garches), all members of the French Association for the Promotion of New Technologies for Disabled People (Approche) in comparison with 24 able-bodied control participants (16 females; mean age: 33 year, range: 19-55 year). Participants were asked to grasp six objects previously placed around their wheelchair using the ARM. They selected the object through the graphic user interface using a computer access method they were comfortable with (12 with trackball, 6 with a simple mouse, and 2 with head tracking). The measurements used were global success rate, completion time in object selection, number of clicks, and satisfaction. Data were analyzed using repeated-measures ANOVA with the group (disability group, control group) as the between-subjects factor, the object/location (6 possibilities) and the trial number (first, second, third), as the within- subjects factors. The significant higher success rate was found in the control group (88.7% for the control group and 81.1% for people with disability). Statistically higher completion time was found in the disability group (71.6s) in comparison with the control group (39.1s). Both groups showed no significant difference in the number of clicks. A high satisfaction rate was reported [2].

A study by the University of Central Florida investigated the utility of using the UCF-MANUS, an ARM designed with two operation modes: manual and autonomous. Ten participants with SCI (mean age: 41.1 year, range: 25-54 year) were divided into two groups to compare the performance of two operational modes in a pick-and-place task for three weeks. Task completion time, number of clicks, command inefficiency and planning inefficiency calculated from trajectory data were used to measure performance, user's effort, and efficiency. A modified Psychosocial Impact of Assistive Devices Scale (PIADS) and an interview were administered as assessment of satisfaction and responses of issues with user interfaces. Results showed a significant reduction in the number of clicks and task completion time in the auto mode group. A learning effect was found in this three-week study. The average completion time and number of clicks were reduced more on the third week in the manual mode group. In contrast, the satisfaction scores in the auto mode group were found to be slightly lower than the manual mode group. The authors concluded that auto mode performed the task easier and faster but less satisfactorily [29].

The University of Massachusetts Lowell conducted a study with 12 participants (4 females; age: 17-60 year; 7 using manual wheelchairs and 5 using power wheelchairs) in testing the performance of a developed vision-based autonomous object-retrieving system. Among the participants, nine participants used a touch screen, one used a touchscreen with key-guard, one used single switch scanning, and one used a head pointer to select an object on the display in front of them. The task was to select an object of the researcher's choice and have the robotic manipulator recognize and retrieve the selected object from a shelf. Mood rating scales were recorded before and after a task session. A post-session questionnaire was conducted after the task. Psychometric measurements were the pre- and post-session mood rating scales, post-session questionnaires, and a shortened version of the Psychological Impact of Assistive Devices Scale (PIADS). Performance measurements were the time for user selection, gross motion, visual alignment, object identification, fine motion, grasping, and return of the object to the participant. User selection time included perception time (i.e., time in identifying the object location on the shelf and on the display), and motor time (i.e., time in selecting the object on the display). The autonomous system success rate was 65% in 198 trials. The averaged total time was 164.72±61.71s. However, in the comparison between four cognition levels of the perception time and PIADS, the authors used one-tail t-test without any adjustment. Therefore, there might be risks for inflation of type I error in the reported p value [7], [27], [35].

A study with 27 participants by the Center for Interdisciplinary Research in Rehabilitation and Social Integration (CIRRIS) evaluated the usability of the JACO robotic manipulator. Among the 27 participants, 22 participants (4 females, mean age: 40±16.4 year, years in WC: 16.5±13.5 year) completed the evaluation tasks. First, the participants performed 16 basic movements twice as easy tasks. These 16 movements include all possible actions of the ARM: touching targets located left, right, up and down; rotating the hand; pushing objects; activating the grasp function; placing the arm in its retracted position. Six more difficult tasks were performed for the evaluation with the JACO arm mounted on the tabletop: 1) grasping a bottle located on the left side on the table; 2) grasping a bottle located on the right on a surface near the ground and bringing it on the table; 3) pushing the buttons of a calculator; 4) taking a tissue from a box on the table; 5) taking a straw in a glass on the table; and 6) pouring water from a bottle into a glass. Participants were asked to perform each task twice successfully and the success rate to achieve two trials was recorded. The success of the trials is defined by the full completion of the testing tasks. Perceived mental loading and importance were surveyed using a 4-point ordinal scale. A socio-demographic questionnaire was also used. The success rate for easier tasks was more than 95% (the 16 movements) and for tasks 1-6 that are more difficult was more than 80%. On the perceived easiness scale, it was reported that taking a tissue is the easiest and grasping a bottle from the ground and putting it on the table was the hardest. Pouring out bottled water into a glass was rated the highest importance and pushing a calculator’s buttons was rated low importance [28].

A larger sample sized (n=31; mean age: 45.6±14.7 year) study of the JACO manipulator reported a similar success rate, easiness, and importance. In addition, estimated time saved in eating, drinking, preparing meal, dressing, and washing was calculated from self-reported time [16].

The Personal Mobility and Manipulation Appliance (PerMMA) developed by University of Pittsburgh consists of manual, tele-operation, and autonomous operation modes. PerMMA, equipped with two Manus ARMs by using combinations of the three modes and two types of user interface: touchscreen for the local user and haptic devices (Phantom Omni by Sensable) for the teleoperation user [30]. This study recruited 15 participants (6 females; mean age 42.9± 15.8 year) with both upper and lower extremity impairments and using power wheelchairs to evaluate the performance within a laboratory environment. Participants were asked to complete as many of five tasks independently using the touchscreen interface and in cooperation with a teleoperator. The five tasks were 1) retrieving a piece of tissue from a tissue box on a desk; 2) picking up a meal container with a flexible handler from a desk and putting it down at a predefined new location; 3) opening a microwave oven by pushing the door button; 4) retrieving a plastic cup and moving it close enough for the user to drink; and 5) retrieving a straw and putting it into a plastic cup, and picking up the cup and moving it close enough for the user to drink with the straw. Task completion time was recorded. An interview of preference of operation modes was conducted after finishing the tasks. Although the results showed that teleoperation mode was much faster, in the interview after performing all tasks, participants indicated they preferred to operate PerMMA independently.

2.3 ICF CODE EVALUATION

In this section, the reviewed articles are summarized using the ICF codes. The ICF, released by the World Health Organization (WHO) in 2001, provides a comprehensive view of health status from different perspectives: Body Functions, Body Structures, Activities and Participation, and Environmental Factors. Body Functions and Structures express physiological functions of body systems and anatomical elements such as organs, limbs and their components. Activities describe the execution of a task or the actions by an individual. Participation is the involvement in life situations. Environmental Factors consist the physical, social and attitudinal features [36]. The evaluation tasks with ICF codes and measurements in these studies are presented in Table 3.

Table 3. List of number of reviewed articles that performed evaluation of the certain ICF code.

ICF code	Number of reviewed articles (Percentage)
d4452 Reaching	**20 (18.02%)**
d4400 Picking up	**18 (16.22%)**
d4300 Lifting	**16 (14.41%)**
d430 Lifting and carrying objects	**11 (9.91%)**
d4305 Putting down objects	**8 (7.21%)**
d560 Drinking	**7 (6.31%)**
d550 Eating	**5 (4.50%)**
d4453 Turning or twisting the hands or arms	**4 (3.60%)**
d2100 Undertaking a simple task	**3 (2.70%)**
d445 Hand and arm use	**3 (2.70%)**
d4401 Grasping	**2 (1.80%)**
d5100 Washing body parts	**2 (1.80%)**
d5202 Caring for hair	**2 (1.80%)**
d630 Preparing meals	**2 (1.80%)**
d640 Doing housework	**2 (1.80%)**
d3352 Producing drawings and photographs	**1 (0.90%)**
d3601 Using writing machines	**1 (0.90%)**
d4450 Pulling	**1 (0.90%)**
d4600 Moving around within the home	**1 (0.90%)**
d5201 Caring for teeth	**1 (0.90%)**
d6506 Taking care of animals	**1 (0.90%)**

The ICF codes and domains help the researchers identify and develop the functioning of evaluation tasks. Although the ICF codes do not list all the tasks in detail, the domains and codes can be used as the basic functioning activities to be evaluated with ARM in order to increase independence. The majority of the ICF codes of the evaluation tasks in the reviewed studies is picking up, reaching, putting down, or lifting in the Mobility domain (Table 3). In a study that monitored an able-bodied person for five days, Lifting and putting down objects are the most frequent activities [37]. Accelerating and facilitating the control for these highly frequent motions would show significant improvement of entire task performance. On the other hand, simulated eating and drinking tasks in the Self-Care domain are also evaluated in some studies. These are the basic movements for completing complex work or tasks. In comparison with the priority list from pre- and post-development and non-users, there are still some highly rated activities in the Activity and Participation domain that have not been explicitly explored yet. Those with more complex tasks, such as d630 preparing meals, d640 doing housework, d3352 producing drawings and photographs, d3601 using writing machines, or d6506 taking care of animals, could be included in future ARM studies.

Using the ICF codes as a reference reveals the insufficiency of evaluation tasks in current ARM studies. Further improvement can be shifted to focus on functioning activities such as drinking, vocational related work, or simple housework other than pick-and-place tasks or evaluations using clinically valid and reliable outcome measures that are relevant to these ICF codes.

2.4 CHALLENGES IN ARM PERFORMANCE ASSESSMENT

Task completion time is the most commonly used measurement in the performance evaluation of user interfaces. Improvement can be caused by faster robot speed, shorter and smoother trajectories, learning effect, easier tasks, lager target size, easier grasp orientation, reduced mode change error, better user interfaces or better sight of view etc. Therefore, it may not be directly related to deficiencies or perceived difficulty in the movement. For example, grasping a bottle on the table without many objects around is much easier than grasping it deep inside the refrigerator. This integrated outcome measure would not be specific enough for researchers to determine which part makes the task difficult. Thus, to determine the performance of human-robot interaction, the following concepts may need to be taken into consideration.

First of all, standardized ADL task performance evaluation is needed so that different research groups can replicate these tasks. These standardized ADL tasks consist specific starting and ending positions, and different target sizes, etc. The specific starting and ending positions constrain the distance of the tasks. In this way, the idealized trajectories can be defined as the straight line from starting position to the ending position. These idealized trajectories are the most efficient path in completing the tasks. Different sized targets facilitate to compute Fitts' parameters and difficulties in using different user interfaces [38]. In addition, the standardized ADL tasks can be utilized as a reference for training and evaluation procedure once the user received the ARM.

Second, using widely accepted valid and reliable functional assessment tests help provide stronger clinical evidence and efficacy in performance evaluation. In the reviewed studies, several function assessment tests [23] with modified protocols or subtests were evaluated, but the ARM performed significantly slower with large variance. This might be due to the small sample size (n=9), different types of user interface, cognitive ability, or lack of feedback and DOF limits in the user interface. For example, in the modified Minnesota Rate of Manipulation Test, the subject has to flip the checker and align it into another hole. This motion is the combination of pick-and-place and peg-in-hole tasks that able-bodied can perform in seconds by taking the advantage of visual and tactile feedback, and movement with simultaneous rotation and translation. However, robotic manipulators do not provide force feedback, simultaneous movements in translation and rotation. Subjects can only perform the test based on the visual feedback and switching between different control modes, which make the test difficult to complete. Moreover, although the test is clinically accepted, the task is not directly related to ADLs, which makes users less motivated to perform. Therefore, it is important to choose appropriate ADL-relevant functional assessment tests for performance evaluation with taking the design of robotic manipulators into consideration.

Third, the Fitts' parameters and trajectory analysis help to more accurately assess the performance while eliminating the influences from distance, target sizes, and environmental variance between tasks and studies. Single action tasks can be represented with Fitts' indices of difficulty. In this approach, different tasks with the same user interfaces can be integrated. For example, task of touching one larger sized target, lower index of difficulty, can be integrated with touching the smaller target, which has a higher index of difficulty. This approach also helps to evaluate ARM performance under various indices of difficulty to better understand the limitation in the ARMs and their user interfaces. One example is that a faster ARM may be efficient with larger target, but have to deal with overshooting problems with small targets.

Lastly, most studies follow the concept of user-centered design or “consumer in the loop” design. However, best practices would be not only to interact with the real end-user, but also the extended users such as family members, therapists, physicians, administrators, caregivers, and others who would influence the usage of the new developed technologies. ARMs may interact with tangible objects most of the time; however, intangible interaction with these indirect users and discussion of topics such as social aspect or aesthetics would give researchers broader point of views for their design or development [39].

This chapter includes the development and evaluation of ARMs, including desktop- and wheelchair-mounted robotic arms. The list of desired tasks from a target population during the pre-and post-development, non-users like family members and caregivers, and end-users in long-term use studies were discussed and provided with associated ICF codes. The performance evaluation measurements were discussed. The associated ICF codes of the tasks used for evaluation are also reported.

Task completion time provides a reliable outcome measure to task performance only when the task is well defined to eliminate variation between tasks. In this research work, we developed a standardized ADL tasks performance evaluation tool for quantitatively and qualitatively evaluating task efficiency and performance, which can be compared between other research groups. In addition, we have also modified a clinical functional assessment tests with consideration of capability and constraint in ARM user interfaces. Consequently, these reliable and valid outcome measures will help clinicians and therapists build clinical effectiveness while prescribing and assessing ARMs.

Technological development has made ARMs more efficient and easier to use. Vision-based autonomy with path planning demonstrates tremendous reduction in user loading of adjusting and twisting the end-effector to the desired grasping position. However, users are isolated from participating in accomplishing the task, which leads to lower satisfaction. In this research work, we will introduce one improvement in developing a shared user interface between higher dexterity autonomous ARM control function with operated by manual user interfaces. It would reduce the required DOF for pick-and-place tasks since only few moves can finish a complex sequential task.

3.0 DEVELOPMENT AND VALIDATION OF ADL PERFORMANCE EVALUATION TOOL

3.1 INTRODUCTION

As mentioned earlier in section 2.1.4, Challenges in ARM Performance Assessment, lack of standardized performance tests would be the major barrier in establishing systematic clinical evidence. Two review articles [40], [41] suggested using existing standards or clinical functional assessment tests as a measurement tool. One option is to use clinically valid and reliable performance-based functional assessment for upper extremities [31]. Another option is to follow the standards in the International Organization for Standardization (ISO). Although there is no specific ISO standard designed for ARM user interfaces, we follow the Performance Testing section of the ISO 9241-9 [42] guidelines, Requirements for Non-keyboard Input Device, to evaluate ARM performance because most manual user interfaces are similar to physical input devices. The evaluation is based on the Fitts' law [38] to exam the human-robot interfaces. The ISO 9241-9 have further been used to evaluate three dimensional input device in studies [43], [44] by adjusting the computation of the index of difficulties and provides a standardized parameter, throughput, as a performance indicator between types of interface.

In order to improve the accuracy and reliability of task evaluation, we follow the design concept from the National Aeronautics and Space Administration (NASA), who developed various task boards to evaluate robot performance for teleoperation [45], [46]. The performance was evaluated by manipulating switches, connectors, and mechanical components mounted on an exchangeable task board.

Therefore, in combining all these ideas together, we developed an ADL task board with different sized components used in ADL. This chapter will introduce the development of standardized ADL performance evaluation tool and conduct clinical studies that compare ARM user interfaces that can be included to quantify performance of ARMs in the clinical training and assessment process.

3.2 DEVELOPMENT OF THE ADL TASK BOARD

3.2.1 System Overview

3.2.1.1 Hardware

Based on the ISO 9241-9 standards, we have developed a portable ADL task board [32] as a tool for researchers to compare user interfaces, clinicians to train or evaluate performance, and ARM suppliers to collect justification data during home evaluation. The ADL task board system consists of six electronic components selected from commonly performed ADL tasks, including one large size circular button similar to a door opener, one small size circular elevator button, one rectangular shape rocker light switch, one toggle switch, one door handle, and one knob. These components simulate usual home and community activities such as turning door handles, turning knobs on the oven, using the elevator or door opener in the communities, and turning on or off light switches at home. The door handle and knob tasks are linked to potentiometers to measure their rotation angle. Aside from these six components on the task board, a square sized button is connected to the task board that sits on a table as the test starting location. Moreover, three LED lights on the large, small, and start buttons are implemented to provide visual indications when buttons are pressed correctly. The task completion time is computed from the release of the start button to the turning on of target buttons/switches or achievement of the desired angle of the target rotational components.

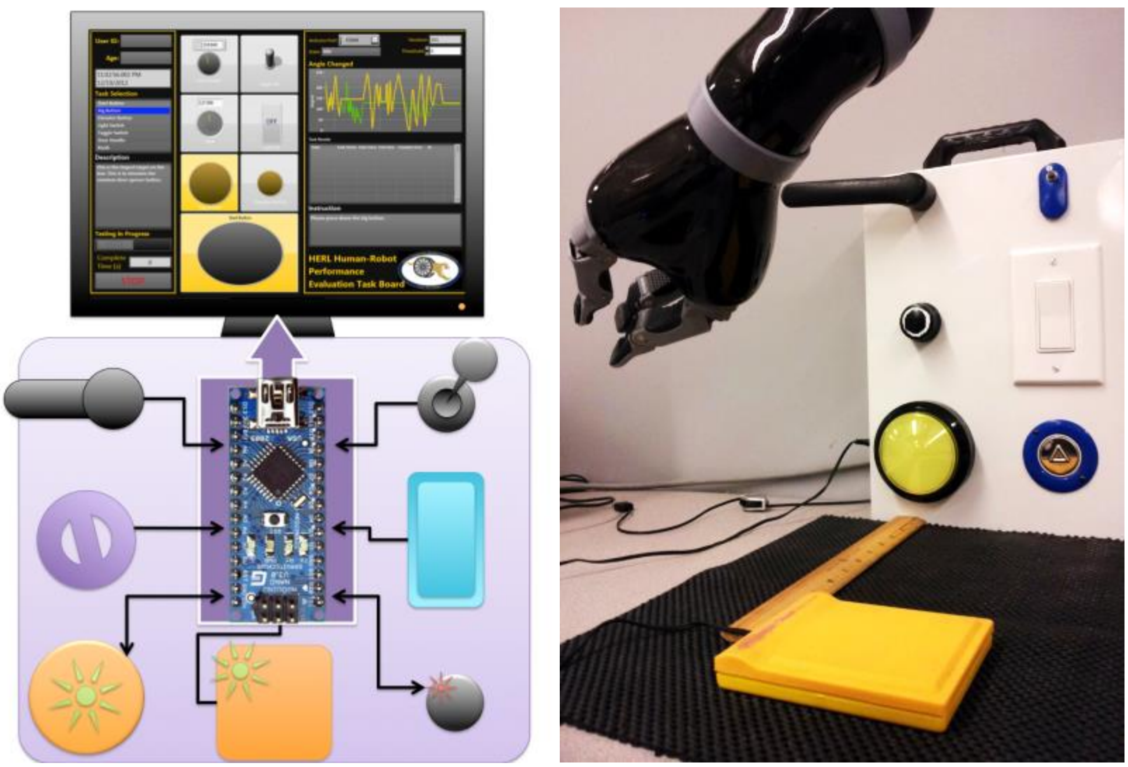

Figure 6. ADL task board system

3.2.1.2 Software

A user-friendly data acquisition interface is integrated into the system. Figure 6 shows a photograph of the ADL task board system. The data acquisition software monitors and collects the interaction of the components on the ADL task board. The data acquisition was developed using LabVIEW control software with interface to an Arduino toolkit, and an Arduino Nano micro-controller board. Figure 6 shows the block diagram of the data acquisition system. The software allows the test administrator to select the task. Descriptions and instructions present after the task is selected. The software timer starts after the start button is released to the OFF state and stops when the target button is pressed to the ON state or the target potentiometer rotates to the preset angle. The task completion time is recorded. The front panel of the data acquisition software is shown in Figure 6.

3.2.2 ISO 9241-9 Index of Difficulty and Throughput

ISO 9241-9 throughput is based on Fitts' law. Fitts' law is used to model the performance of human-computer interaction in rapid movement as a function of distance to the target and the size of the target. The comparable parameter to throughput for the user interface in bits per second (bits/s) is defined by,

$$Throughput = ID / MT$$

MT is the movement time or the task completion time in seconds and *ID* is the index of difficulty in bits. For all trials within the same condition, and, different from the *ID* in Fitts' law, the *ID* in ISO 9241-9 is defined as [42],

$$ID = \log_2\left(\frac{D}{W_e}+1\right), \text{ where } \mathrm{W_e} = 4.133 \times \mathrm{SD},$$

D is the distance to the target, and W_e is the effective width computed from the task end point from movements, *SD* is the standard deviation of the target end points, which is modified for 3D task as [44],

$$SD = \sqrt{\frac{\sum_{i=1}^{n}[(x_i-\bar{x})^2+(y_i-\bar{y})^2+(z_i-\bar{z})^2]}{n-1}}$$

It can be seen that the throughput is an integrated variable that associates with task difficulty and task completion time. It indicates the user interface's efficiency in performing tasks. For example, if performing different tasks, the user interface with lower *MT* or higher *ID* leads to higher throughput, which means the user interface is more efficient even performing more difficult task. Therefore, we can compare user interfaces only use the throughput because this value generalizes the human-computer interaction performance.

3.3 DEVELOPMENT OF ADAPTED WOLF MOTOR FUNCTION TEST

As discussed in Chapter 2, a clinically accepted performance evaluation test facilitates establishing clinical effectiveness. In this section, we will introduce an Adapted Wolf Motor Function Test for ARM (WMFT-ARM), which uses daily objects that can be easily obtained at home or clinic. The WMFT-ARM will allow clinicians to quickly identify and evaluate the ARM and its user interface that clients prefer and provide a way to quantify and qualify outcomes of their interventions.

3.3.1 Adapted Wolf Motor Function Test for the ARM

The WMFT-ARM is adapted from Wolf Motor Function Test (WMFT). WMFT is a clinically reliable and valid measurement tool that involves timed function tasks associated with ADL for upper extremity performance evaluation [47]. The original WMFT [48] contains 17 tasks. However, while adapting to ARM usage, some tasks are not applicable to the configuration and capability of the ARMs. For example, the task of folding towels requires two hands moving synchronously, which is not applicable to the user with single ARM. In addition, some objects such as pencils can be replaced by mouth sticks if the ARM user does not have fine muscle movement to control a pen or pencil and paper clips can be replaced as keys with/without key adaptors, which is similar in thickness but more common in wheelchair users. The testing procedures were established based on the tasks listed in Table 4. Table 4 identifies the task, setup for the task, the specific task itself, and verbal instructions for completion of the task. Figure 7 and Figure 8 shows the testing objects and setup of WMFT-ARM.

Figure 7. Left: ARM user interfaces and instructions; Right: The daily objects that can be used for the WMFT-ARM – soda can, mouth stick, lock or keyhole, key, and pad

Table 4. WMFT-ARM task items, set up, description and instructions

Task Item	Setup	Task	Verbal Instructions
1. Robot hand to table	The ARM is in home position away from the pad	Move robotic hand to the pad	On “Go”, move robotic hand to the pad
2.Hand to box (top)	The ARM is resting on the touchpad and the box is positioned to the right of it on top of the table	Move robotic hand to top of box	On “Go”, position the hand from the start point to the top of the box
3.Weight (12oz beverage) to top of box	Beverage is grasped with the ARM while resting on the pad with a box to the right of it	To place the 12oz beverage on top of the box to the right of it	On “Go”, place the 12oz beverage on top of the box
4.Position beverage to mouth	Beverage is grasped with the ARM while resting on top of touch-pad	To position the 12oz beverage 1” in front of the subjects mouth	On "Go", position the 12oz beverage to your mouth
5.Lift mouth stick	Position the mouth stick on the touch pad while the ARM is in home position	To lift the mouth stick from the touch-pad	On "Go", lift the mouth stick from the touch-pad
6.Lift up key	Place on the table in front of the ARM while the ARM is in home position	Lift the key from the table	On "Go", lift the key from the table
7.Turn key in lock	With the key in the lock, the ARM positioned directly on top of the key ready to grasp it	Grasp the key, turn it clockwise 90˚, then counter-clockwise 90˚	On "Go", grasp the key, turn it 90˚ clockwise, then 90˚ counter-clockwise
8.Lift Basket	The basket will be placed on a surface lower than the table and to the right, with the ARM in home position	Lift the basket from the lowered position and place it onto the table directly in front of the ARM base	On "Go", pick up the basket, and place it on the table in front of the ARM

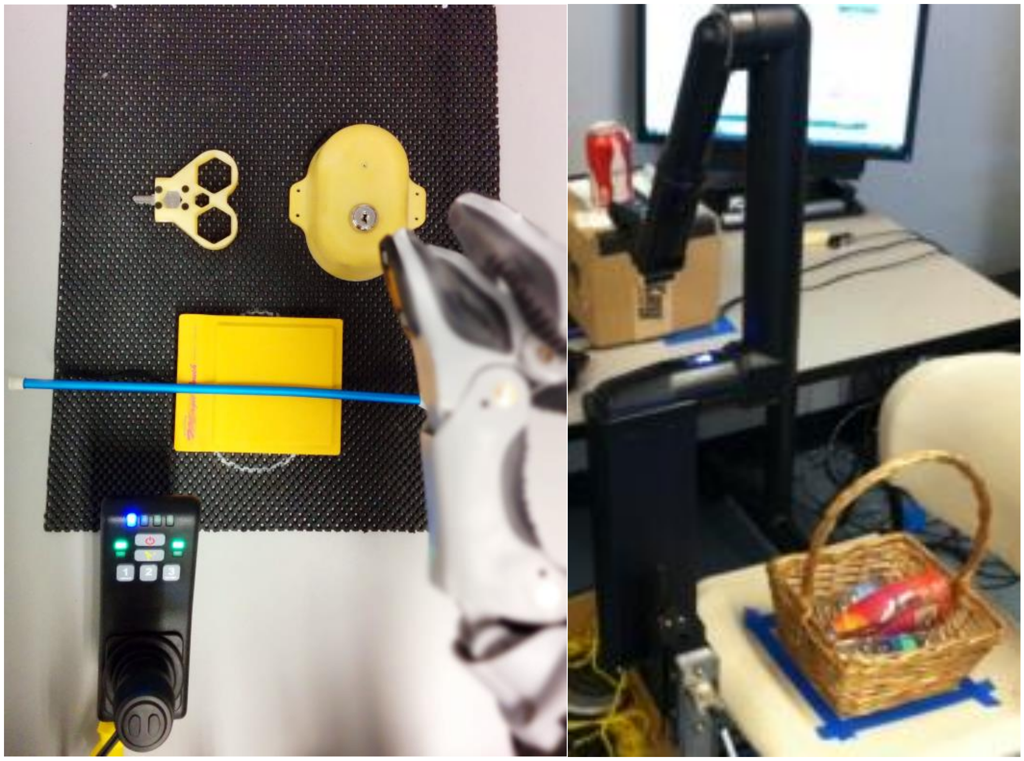

Figure 8. Left: Setup for pick up mouth stick; Right: Setup for lift the basket onto an elevated surface

3.3.2 Intra-Rater Reliability

We examined the reliability of the WMFT-ARM with a trained rater. All the tasks were pre-programmed on the ARM in order for standardization in timing from start to completion of the designated tasks. A trained rater administrated the WMFT-ARM and a researcher executed the pre-programmed trajectories. The ARM trajectory data were recorded as a comparison in completion time. We performed the WMFT-ARM three times. Two tests were performed on the same day with four hours in between and the other one was on a different day with eight days in between.

We analyzed the task completion time using Bland-Altman plot (Figure 9) to demonstrate the differences from ARM data and the rater. The mean difference is -0.04 and the 95% limit of the agreement are 1.09 and -1.16.

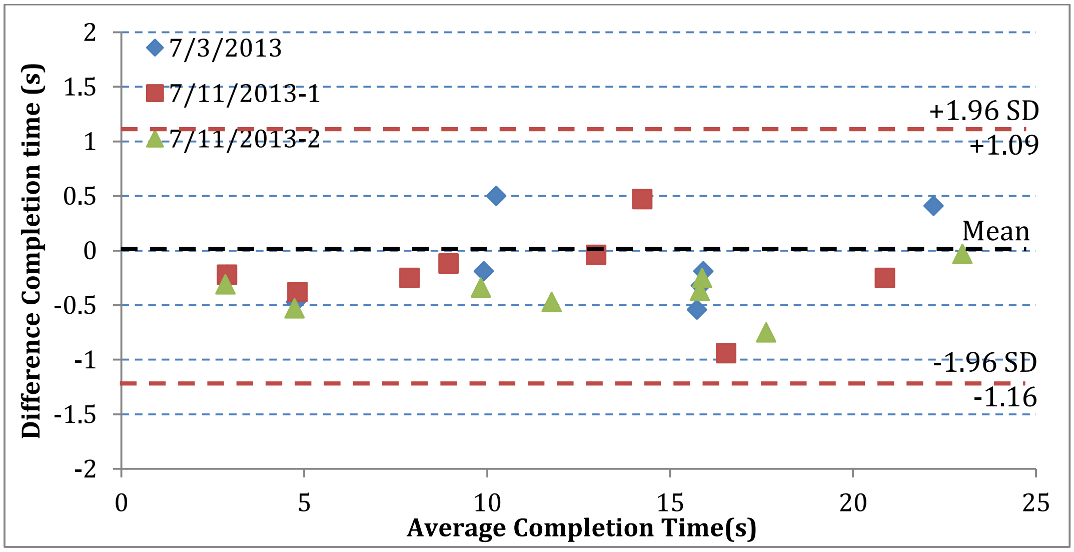

Figure 9. Bland-Altman plot of the trained rater with ARM data

In addition, the intraclass correlation between the same-day and different-day measurements for the single rater was computed. The ICC (2, 1) on the same day was 0.982 (p<. 001) and different day 0.991 (p<. 001). Excellent Bland-Altman plot agreement and intraclass correlations indicated that the rater was reliable. The results also suggested that it should avoid the same day testing because of the reduced ICC (2, 1) probably caused by the weariness.

3.4 CONCLUSION

In this Chapter, we have described the ADL task board evaluation tool that provides standardized ARM performance and environmental independent Fitts' parameters, the ISO 9241-9 throughput. In addition, WMFT-ARM was adapted from a widely clinical functional assessment tool. With only single rater for the following study, the rater demonstrated excellent intra-rater reliability.

4.0 PERFORMANCE EVALUATION OF COMMERCIAL ARM USER INTERFACES

4.1 INTRODUCTION

In this chapter, we conducted a study that evaluates the performance of current commercial ARMs with their original user interfaces using the ADL task board and WMFT-ARM developed in the previous chapter. For the first time, the commercial ARMs with their original user interfaces were evaluated within the same environment and a standardized evaluation tool to compare the performance and perceived loading. In the comparison between ADL task board and the widely used clinical assessment, Wolf Motor Function Test, we further examined the sensitivity and responsiveness to the changes in ARM user interfaces.

4.1.1 Hypothesis

Hypothesis 1: Participants using JACO's joystick and iARM's keypad user interfaces will complete six tasks on the ADL task board and WMFT-ARM with statistically different task completion time, number of errors, ISO 9241-9 throughput, and trajectory parameters.

Hypothesis 2: Participants will rate the joystick and keypad user interfaces with statistically different cognitive workload.

4.1.2 Human Subjects

Twenty able-bodied participants and ten wheelchair users were recruited to evaluate ADL performance with two commercial manual user interfaces. The reasons to include able-bodied individuals were to minimize individual differences in various degrees of physical impairments and ARM experiences so that we may acquire a homogeneous sample without complex impairments.

4.1.3 Inclusion and Exclusion Criteria

4.1.3.1 Inclusion Criteria:

Control subjects: Participants have to be 18 years older.

Case subjects: Participants must be 18 years older using a powered wheelchair for primary means of mobility, and be able to operate a joystick.

4.1.3.2 Exclusion Criteria:

Control subjects: Participants with hand or wrist pain will be excluded due to prolonged hand and wrist use in this study.

Case subjects:

Participants with active pelvic, gluteal, thigh wounds, pressure ulcer in these regions within the past 30 days will be excluded due to prolonged sitting in this study. Participants with a significant cognitive disability that would preclude them from providing informed consent. The study investigators have extensive experience working with people with disabilities and was able to make this determination when communicating with the potential subject during enrollment. The study was conducted in a controlled environment at the Human Engineering Research Laboratories (HERL). The study protocol was approved by the Institutional Review Board (IRB) of the University of Pittsburgh.

4.2 EXPERIMENTAL PROCEDURES

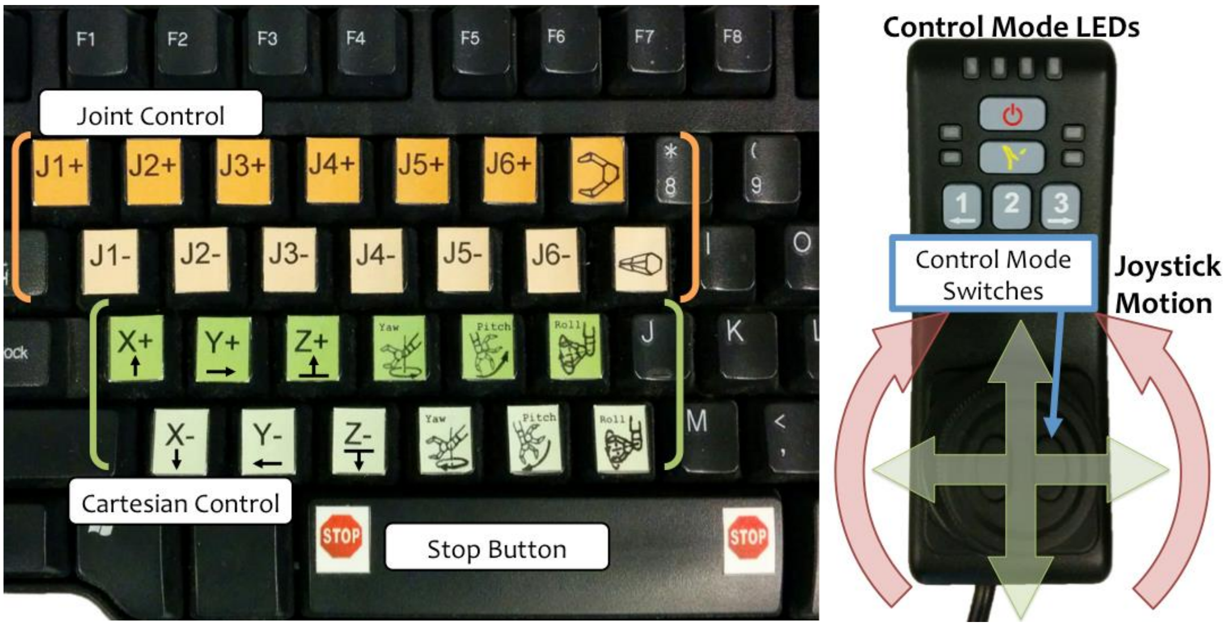

Figure 10. Two user interfaces used in the study

In the control group, there was only one study visit lasting approximately 3 hours. For the wheelchair user case group, there was one study visit lasting approximately 4 hours due to additional WMFT-ARM test.

After informed consent was obtained, general demographic (i.e. age, gender, ethnicity) and educational background were then recorded. Participants were randomly assigned to a manual user interface (Figure 10). The participants were then introduced to the first user interface. This introduction lasted approximately 30 minutes and included a demonstration and hands on practice period with each ARM (Figure 11). A questionnaire regarding the perspective of the ARM user interface was collected before hands on practice and testing. Each participant was given abundant time for the hands on practice until feeling confident with the given user interface. The participants would first try several basic movements such as up and down, or left and right to get familiar with the interface. Then the participants would pick one or more of the task either on the ADL task board or items used for WMFT-ARM for practice. After the participant felt ready for the testing, we then started with the ADL task board performance evaluation. Each participant was asked to complete up to 6 tasks on the ADL task board 3 times each with both user interfaces for a maximum total of 36 trials. The order of the original ARM user interface used and tasks completed were randomized. However, if the time exceeded 5 minutes or the participant expressed frustration, the task was terminated. It was considered a protocol deviation (http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3487227/) if a participant was unable to complete all tasks within the given time frame. Time to complete each task and the trajectory of the ARMs were recorded during testing. Participants were asked to complete the NASA TLX [49] and a questionnaire regarding the user interface after the completion of each series of tasks using one user interface. Following the completion of all 6 tasks with both user interfaces, a brief questionnaire and open interview related to use of the interfaces were then conducted.

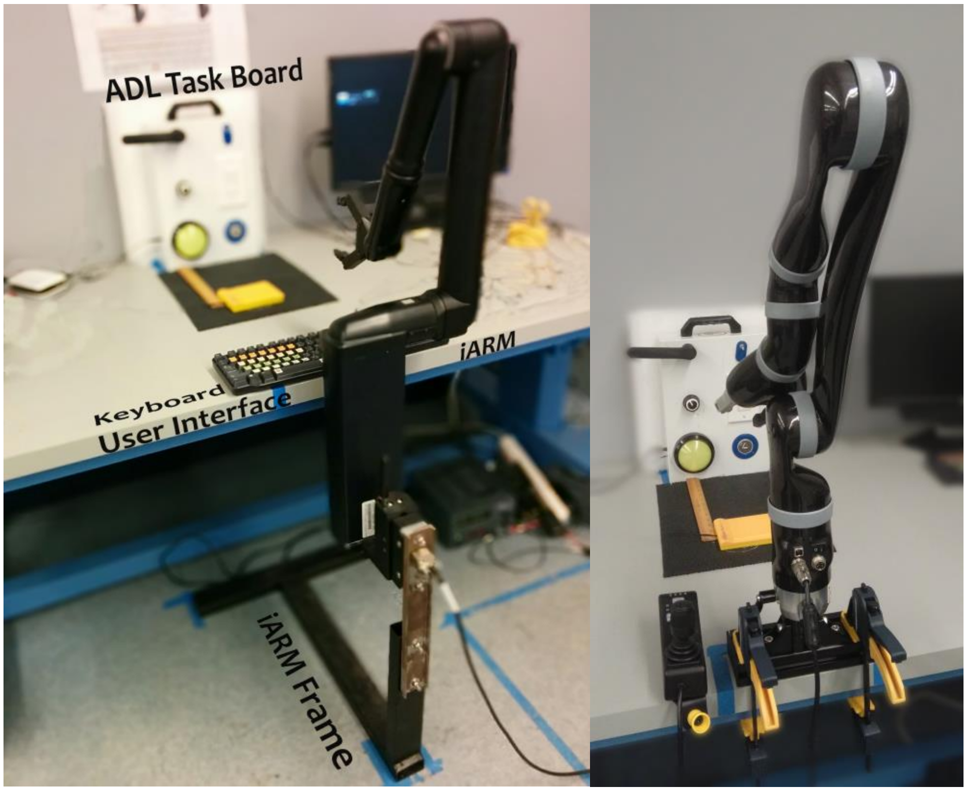

Figure 11. Subject testing set up for the iARM and JACO ARM

For the powered wheelchair users, an additional questionnaire, QuickDASH [50], was administrated after the demographic information to identify the upper extremity function. The WMFT-ARM was performed after the ADL task board test for each manual user interface.

4.3 MAIN OUTCOME MEASUREMENT

4.3.1 Demographic and Interview Questionnaire

The questionnaire for demographic information and interview is attached in the Appendix A. The demographic questionnaire obtained basic information such as gender, age, race, type of disability, and the attitude toward ARM technology such as appearance, easiness in learning or operation. 10-point Likert scale was used to evaluate the accuracy to the statements in the questionnaire (ten indicates extremely accurate and one means not accurate at all). The interview questions include suggestion for user interfaces and ARM, places or tasks that will use ARM.

4.3.2 QuickDASH

The QuickDASH (Appendix B) is a shorter version (eleven items) from the thirty-item DASH (Disabilities of the Arm, Shoulder, and Hand) outcome measurement. It is a reliable and valid tool to measure physical function and symptoms related to upper-limb musculoskeletal disorders [50]. Each item is scored from 1 to 5, which indicate no difficulty, mild, moderate, and severe difficulty, and inability. At least 10 of the 11 items must be completed for a score to be calculated. All completed responses were converted to a comparable scale from 0 to 100. A higher score represented greater disability.

From the QuickDASH instruction, generally, score ranging from 0 to 29 was viewed as "no longer considering their upper-limb disorder a problem." A score ranging from 40 to 69 represents "having a lot of difficulty."

4.3.3 NASA-TLX

The NASA-TLX (Appendix C) is a reliable tool for subjective evaluation of ten workload-related factors [49]. We use an online version at http://tlx.playgraph.com/ [51]. The NASA-TLX consists perceived workload on six different scales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. Participant first rated these six scales and then weighted with 15 pairwise comparisons to increase the sensitivity of workload score and decrease between-rater variance. Higher scores indicate higher workload was contributed.

4.3.4 Task Completion Time and ISO 9241-9 Throughput

The ADL Task Board system provides the task completion time, which is used to compute ISO 9241-9 throughput. The task completion time is measured from the release of the start button to the ON/OFF state change of the target component. The ISO 9241-9 throughput [42] is described in section 3.2.2

4.3.5 Trajectory Analysis

In order to describe the characteristics of the ARM movement and user's familiarity with the user interface, several trajectory parameters were computed: pause percentage, number of pauses, average pause time, roughness, and average speed. The recorded trajectories were analyzed using Matlab R2014a (Mathworks).

The parameters related to pauses help to discover the continuity and potential difficulties that the user encountered such as re-planning for error correction, fine movement, verification of end-effector position, searching another key on the keypad user interface, and switching modes on the joystick user interface. An increasing number of pauses may be caused by more errors or more keys or modes switching in the trial. A pause was defined as the time without movement in the recorded trajectory (time interval: 50 ms). The number of pauses was the number of stops that occurred within one trial. Pause percentage indicates the time when the ARM is not moving in a trial, which is computed as the total pause time over an entire task completion time. The average pause time is computed as:

Average Pause Time = Total pause time / number of pauses

Pauses may reflect the user's decision processing time while completing a task.

The parameter, roughness, is to quantify the maneuvering while in approaching target. It is described as the trajectory's variance compared to a straight line from start to end of a task, which is computed as

$$Roughness = \frac{\sum_{i=1}^{n} dist(p_i, l)}{n}$$

The p_i is the position of the i-th point on the trajectory. The n is the total number of trajectory points. The dist(p_i,l) is the distance from the point p_i to a straight line from the start to the end point, which is assumed as the most effective trajectory. Roughness is used to analyze tasks without secondary movement, such as Big Button, Elev. Button, and Light Switch.

4.3.6 Data Analysis

If the data were normally distributed, one-way repeated measures analysis of variance (ANOVA) was used for the difference between the types of user interfaces with respect to the task completion time, number of pauses, ISO 9241-9 throughput, trajectory parameters, NASA-TLX, and questionnaire items. All the data were examined for normality by Shapiro-Wilk test and checked for outliers using Q-Q plot. Assumption of sphericity was examined by Mauchly's test. If the data were not normally distrusted, then the non-parametric Kruskall-Wallis Test was applied. The level of significance was set at $p < 0.05$ for all comparisons. All these statistical analyses were performed in SPSS (SPSS Inc., Chicago, IL).

4.4 RESULTS

Twenty able-bodied individuals (mean age: 26.7 years old, range: 18-35 years old, 14 males) and ten powered wheelchair users (mean age: 46.3 years old, range: 23-76, 5 males) were enrolled in the study and were tested with two ARM user interfaces. Only two participants had incomplete trajectory data because of the malfunction of the recording computer. All control and case participants were able to complete all the trials successfully.

Table 5. QuickDASH data of the case participants

Item	1. Jar	2. Heavy Household	3. Carrying Shopping Bag	4. Wash Your Back	5. Cut Your Food	6. Recreational Activities	7. Social Activities	8. Work/ Regular Activities	9. Pain	10. Tingling	11. Sleep	Quick DASH Score
Case01	5	5	5	5	5	5	4	5	1	1	1	70.5
Case02	5	5	5	5	5	5	4	3	2	1	1	68.2
Case03	3	4	3	3	3	3	3	3	3	2	4	52.3
Case04	2	3	3	3	2	3	2	2	2	1	4	36.4
Case05	5	4	5	5	5	5	4	4	4	3	1	77.3
Case06	2	2	2	3	2	3	3	3	2	2	1	31.8
Case07	5	5	3	5	3	5	1	4	3	3	3	65.9
Case08	3	5	2	5	2	5	1	2	3	3	2	50.0
Case09	4	5	3	2	1	4	3	2	3	3	3	50.0
Case10	5	3	2	5	2	5	3	3	2	1	2	50.0
Average	3.9	4.1	3.3	4.1	3.0	4.3	2.8	3.1	2.5	2.0	2.2	55.2

The QuickDASH scores (Table 5) indicate that, except for participants #4 and #6, all other participants have moderate to severe upper extremity impairment (e.g., reaching, grasping, holding things, using computer mouse, etc.). Due to the disability in hand dexterity of the first two participants, we used 2-axis mode joystick instead of the original 3-axis mode (Table 6). However, none of the participants had difficulty in using the keyboard. During the testing, Participants 1 and 2 expressed hand and arm fatigue in pressing the rubber button of the joystick interface and requested for a 10-minute break.

Table 6. Demographic data of the participants and user interfaces

Participant ID	Gender	Age	QuickDASH	User Interface*	Education
1	Male	27	70.5	KB, 2-axis JS	Master
2	Male	23	68.2	KB, 2-axis JS	Bachelor
3	Male	57	52.3	KB, 3-axis JS	High School
4	Male	56	36.4	KB, 3-axis JS	College
5	Female	69	77.3	KB, 3-axis JS	Voc. Training
6	Female	26	31.8	KB, 3-axis JS	Bachelor
7	Female	34	65.9	KB, 3-axis JS	College
8	Female	64	50.0	KB, 3-axis JS	College
9	Female	76	50.0	KB, 3-axis JS	Doctoral
10	Male	50	50.0	KB, 3-axis JS	High School

*KB: Keyboard, JS: Joystick

4.4.1 ADL Task Board Results

4.4.1.1 Control Group

Table 7. ADL task board testing results of two user interfaces among control group (Mean±Standard Deviation)

Parameter	Task	Keypad	Joystick	P-value
Average Completion Time (Second)	Big button	24.1±13.9	5.8±2.5	<.001*
	Elevator button	22.1±8.3	15.5±8.3	.021
	Light switch	29.9±16.6	12.9±7.1	<.001*
	Toggle switch	47.5±20.3	15.4±7.4	<.001*
	Door handle	47.9±23.0	29.9±31.6	.008*
	Turning knob	48.6±22.5	52.8±35.0	.640
The Fastest Trial Completion Time (Second)	Big button	14.4±6.5	4.1±1.7	<.001*
	Elevator button	16.0±5.0	10.1±6.7	.004*
	Light switch	20.6±10.9	8.5±5.4	<.001*

Table 7 (continued)

	Toggle switch	32.8±11.3	9.1±4.0	<.001*
	Door handle	31.6±17.0	20.7±25.7	.017
	Turning knob	37.7±20.0	32.0±18.5	.253
Throughput (bit/Second)	Big button	0.091±0.046	0.362±0.153	<.001*
	Elevator button	0.081±0.257	0.132±0.089	.021
	Light switch	0.097±0.050	0.173±0.098	.002*
Roughness (mm)	Big button	49.2±11.8	30.4±12.9	<.001*
	Elevator button	35.8±9.5	42.9±16.0	.010*
	Light switch	58.7±21.6	50.6±17.9	.061
Average Speed (mm/Second)	Big button	63.0±23.6	62.1±20.1	.813
	Elevator button	53.7±16.1	50.0±20.8	.177
	Light switch	69.5±27.0	63.8±22.7	.203
	Toggle switch	53.1±17.3	61.2±17.0	.009*
	Door handle	69.9±29.0	61.7±30.1	.119
	Turning knob	40.4±13.7	27.0±14.2	<.001*
Pause Percentage (%)	Big button	16.8±8.4	12.0±10.8	.009*
	Elevator button	15.0±7.0	20.6±12.7	.009*
	Light switch	15.8±8.4	16.1±14.3	.901
	Toggle switch	25.6±8.9	18.8±11.5	<.001*
	Door handle	21.6±9.7	25.1±15.9	.155
	Turning knob	22.9±8.5	42.3±13.4	<.001*
Number of Pauses	Big button	5.5±4.7	2.7±2.3	.003*
	Elevator button	5.0±2.5	9.8±9.0	<.001*
	Light switch	5.9±4.2	6.0±5.3	.867
	Toggle switch	11.8±7.3	8.4±6.9	.015*
	Door handle	9.2±5.6	12.0±11.8	.105
	Turning knob	10.2±4.4	23.4±13.5	<.001*
Average Pause Time (Second/Pause)	Big button	0.333±0.214	0.297±0.246	.418
	Elevator button	0.286±0.135	0.435±0.338	.006*
	Light switch	0.322±0.187	0.388±0.408	.246
	Toggle switch	0.473±0.180	0.409±0.312	.146
	Door handle	0.483±0.236	0.657±0.434	.011
	Turning knob	0.504±0.296	0.933±0.446	<.001*

* Significant after Bonferonni adjustment ($\alpha = 0.05$)

The results of the task board measurements are listed in Table 7. The joystick user interface was statistically faster than the keypad user interface in four tasks except for elevator button and knob turning. The joystick is slower than the keypad in the average completion time in the knob turning task (Figure 12). By only comparing the fastest trial (Figure 12) of each participant in each task, the joystick user interface was statistically faster than keypad user interface for the same five tasks. Conversely, the average of the fastest trial task completion time with the joystick in Knob was slightly faster than the keypad. On average, about 30-40% of completion time was reduced in the fastest trial of each task. Even though we provided time to practice with the ADL task board, we still found a learning effect with improved performance or small variations among the three trials on the each task (Figure 13). The average speed of both user interfaces was around 50-70 mm/Sec. The keypad was statistically faster with the Knob (p<.001) but statistically slower with the Toggle Switch (p=.009).

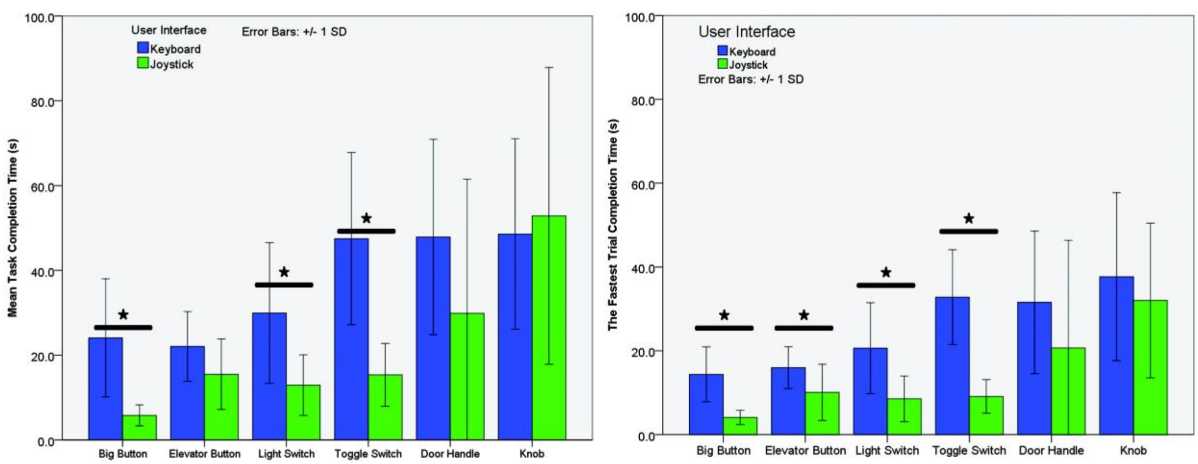

Figure 12. Left: the mean task completion time of the six tasks on the ADL task board in the control group; Right: the minimum task completion time of each participant on the ADL task board in the control group

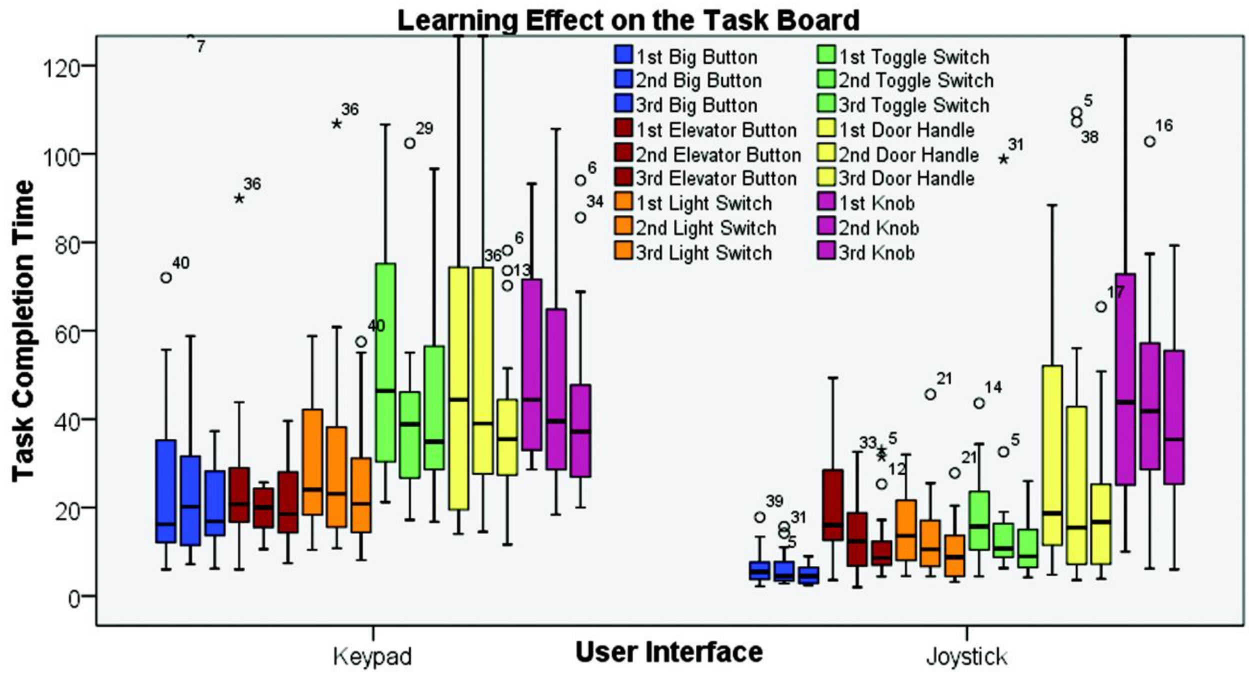

Figure 13. Learning effect of the three trials on the ADL task board among control group

For the single action tasks such as Big Button, Elev. Button, and Light Switch, we compared these tasks using two characteristics: throughput, and roughness. In these tasks, the joystick user interface showed statistically faster motion. Similarly, its throughput is statistically higher than the keypad user interface (Table 7). However, the throughput of the joystick user interface is lower than previously reported results [32] because all the participants in this study were first-time ARM users.

4.4.1.2 Case Group

Table 8. ADL task board testing results of two user interfaces among case group (Mean±Standard Deviation)

Parameter	Task	Keypad	Joystick	P-value
Average Completion Time (Second)	Big button	70.7±67.6	10.7±7.4	.012*
	Elevator button	64.0±57.8	24.9±15.7	.054
	Light switch	90.2±95.0	22.0±12.2	.037*
	Toggle switch	101.3±87.4	22.6±15.4	.020*
	Door handle	75.3±70.4	21.9±13.2	.030*
	Turning knob	116.5±108.9	49.2±28.3	.075
The Fastest Trial Completion Time (Second)	Big button	52.8±59.3	7.2±4.2	.026*
	Elevator button	46.1±40.4	15.6±9.5	.032*
	Light switch	57.9±62.6	11.8±7.6	.033*
	Toggle switch	53.4±48.4	13.4±6.8	.047*
	Door handle	31.6±17.0	20.7±25.7	.018*
	Turning knob	75.6±78.5	23.0±14.6	.052
Throughput (bit/Second)	Big button	0.065±0.074	0.274±0.151	.001*
	Elevator button	0.069±0.219	0.231±0.073	.029*
	Light switch	0.045±0.143	0.121±0.038	.025*
Roughness (mm)	Big button	58.2±26.2	39.6±21.5	.020*
	Elevator button	54.5±27.6	57.8±29.2	.720
	Light switch	71.1±20.8	54.8±27.3	.038*
Average Speed (mm/Second)	Big button	36.2±10.9	45.2±17.8	.071
	Elevator button	34.9±16.2	33.5±17.1	.798
	Light switch	39.2±9.6	46.7±23.9	.191
	Toggle switch	33.2±9.8	39.0±12.9	.116
	Door handle	41.3±17.0	44.2±21.6	.638
	Turning knob	31.4±19.1	20.6±13.6	.061
Pause Percentage (%)	Big button	28.8±11.3	12.6±17.5	.002*
	Elevator button	31.6±12.9	26.0±13.3	.193
	Light switch	29.9±9.2	16.1±12.4	<.001*
	Toggle switch	32.8±11.6	21.4±8.6	.002*

Table 8 (continued)

	Door handle	34.1±10.6	19.6±14.5	.001*
	Turning knob	38.6±11.5	41.6±21.1	.589
Number of Pauses	Big button	9.1±6.4	5.2±7.0	.081
	Elevator button	10.6±5.3	14.5±10.7	.147
	Light switch	11.9±8.0	12.3±11.8	.901
	Toggle switch	13.5±11.9	15.3±17.3	.702
	Door handle	11.1±10.1	9.1±8.1	.504
	Turning knob	16.4±10.2	23.2±21.8	.229
Average Pause Time (Second/Pause)	Big button	0.772±0.351	1.054 ±3.644	.745
	Elevator button	0.823±0.439	0.546±0.293	.027*
	Light switch	0.791±0.366	0.346±0.326	<.001*
	Toggle switch	0.845±0.288	0.566±0.428	.020*
	Door handle	1.018 ±0.388	0.577±0.375	.001*
	Turning knob	1.093 ±0.440	1.134±1.049	.877

* Significant after Bonferonni adjustment ($\alpha = 0.05$)

Among the case participants, the results of the task board measurements are listed in Table 8. The joystick user interface showed statistically faster performance than the keypad user interface in the same four tasks except the elevator button and knob turning. By only comparing the fastest trial of each participant in each task, the joystick user interface shows statistically faster performance than keypad user interface in five tasks except knob turning. Conversely, the average of the fastest trial task completion time among case subjects using the joystick in Knob task was faster than the keypad. On average, about 30-50% of completion time was reduced in comparison of the fastest trial and the average of three trials. Learning effects were also found in the case group. Figure 14 shows improved performance in the three trials. Joystick user interface also shows statistically higher ISO 9241-9 throughput among the case participants in the three tasks, Big Button, Elevator Button, and Light Switch. The average throughputs computed in the first-time user study were 0.065 for the Big Button and 0.274 bit/s for the Elevator Button. In comparison with a study under a 2D work space, a throughput for laptop access of a finger-controlled isometric joystick was reported as 2.07 bit/s [42]. In the 3D working space, a study [44] evaluating human motion in touching virtual objects in an augmented reality environment and reported that the throughputs using different techniques were between 0.54 and 1.13 bit/s. In a study [32], the average throughputs performed by an experienced user were 0.98 in the Big Button Task and 1.17 bit/s in the Elevator Button Task.

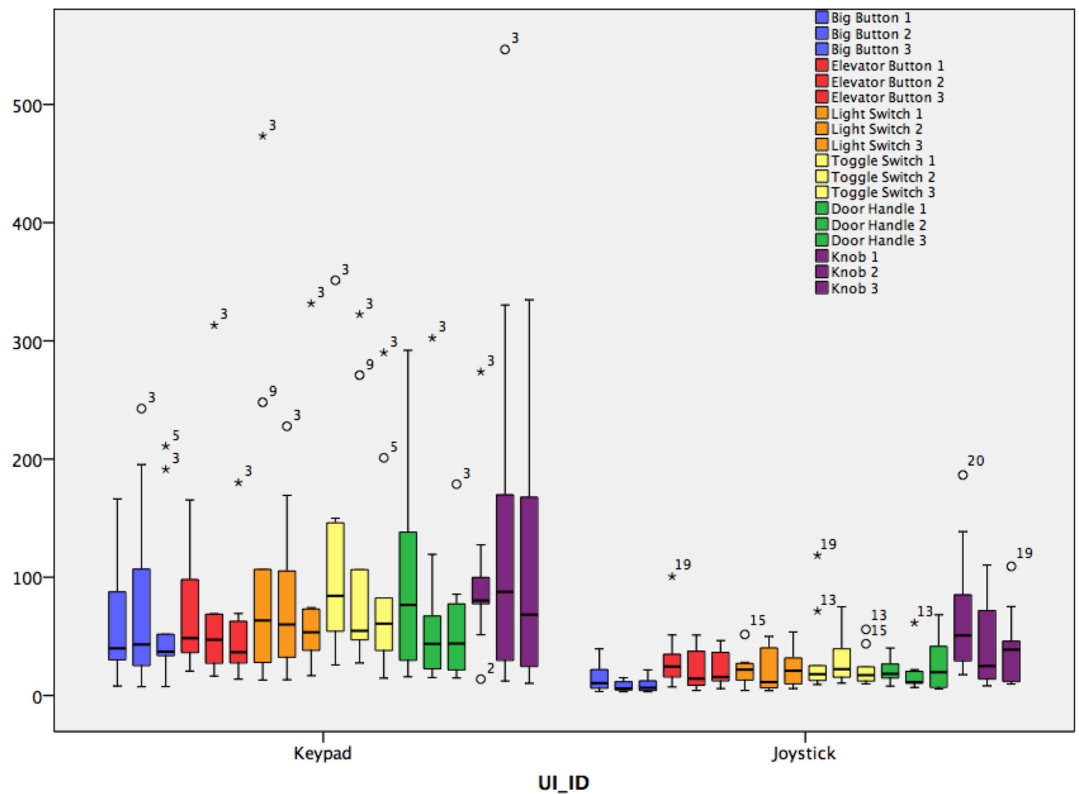

Figure 14. Learning effect of the three trials on the ADL task board among case group

4.4.2 Trajectory Analysis

The joystick user interface showed statistically smaller roughness in the Big Button and Light Switch tasks (Table 8). The keypad user interface showed lower roughness in the elevator button task on average.

The pause percentage shows that overall the users stopped from 12-42% of the time during task performance (Table 8). The pause percentage and number of pauses using the keypad was statistically lower in the Elev. Button and Knob and statistically larger in the Big Button and Toggle Switch. In the comparison of the average pause time, the keypad was under 0.5 second and the joystick is 0.3-0.9 second in all tasks. The keypad was statistically lower in the Elev. Button, Door Handle, and Knob. There were no statistical differences found in the other three tasks. In the comparison to the number of pauses, there were statistically more frequent pauses found in the Big Button, Elev. Button, and Knob in the joystick user interface, but statistically less frequent pauses in the Toggle Switch.

Among the case group, roughness with the joystick user interface was statistically smaller in the Big Button and Light Switch tasks, for smaller sized targets, Elevator Button, there was no statistical difference found in roughness. The average speed of both user interfaces was around 20-47 mm/Sec, which is slower than the control group. No statistical difference was found in the average speed between user interfaces. Pause percentage using the keypad user interface was around 28-38% on average and for the joystick 12-41%. The time per pause using the keypad was statistically larger in four tasks except the Big Button and Knob.

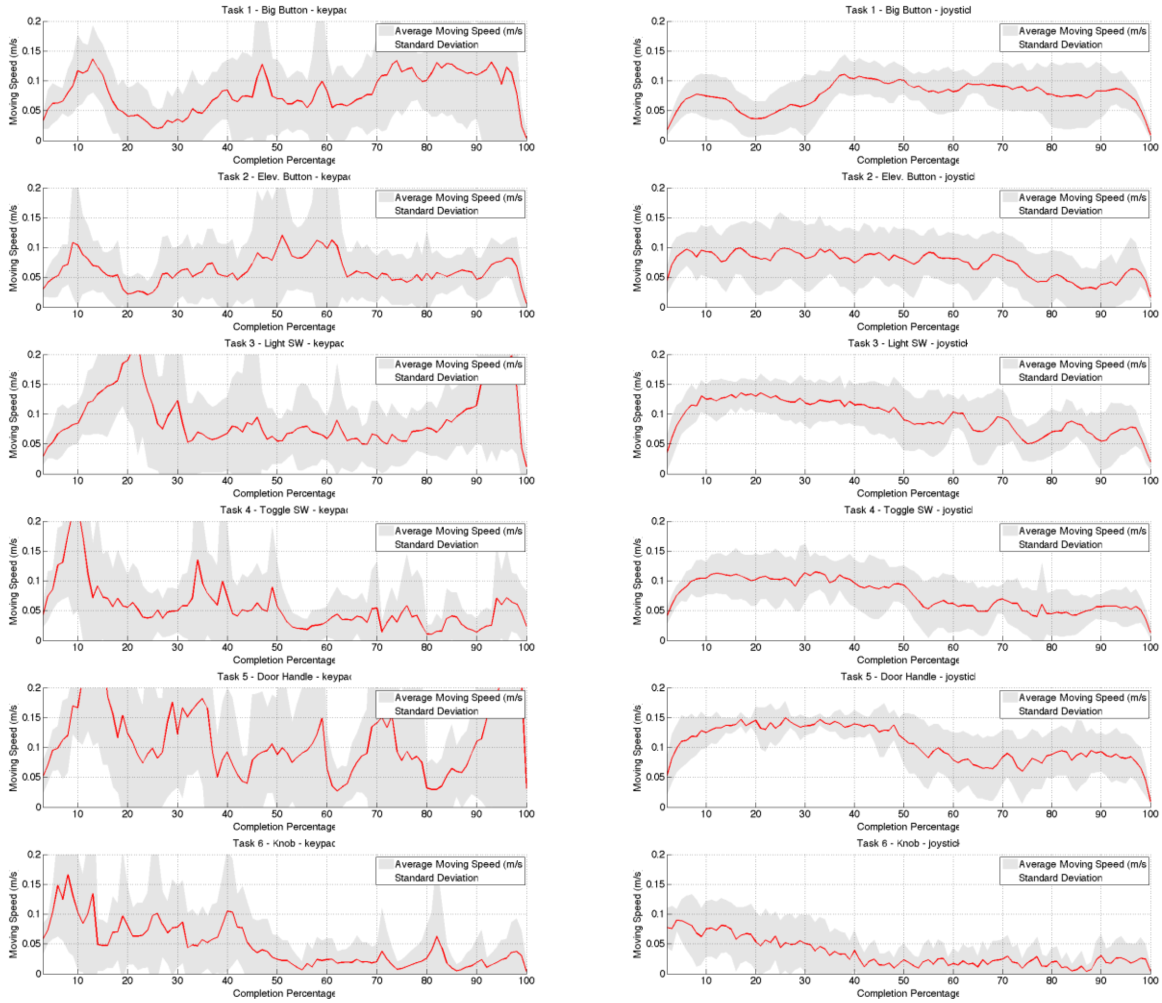

Figure 15. The moving speed of the fastest 10 trials of the control group (left: keypad, right: joystick).

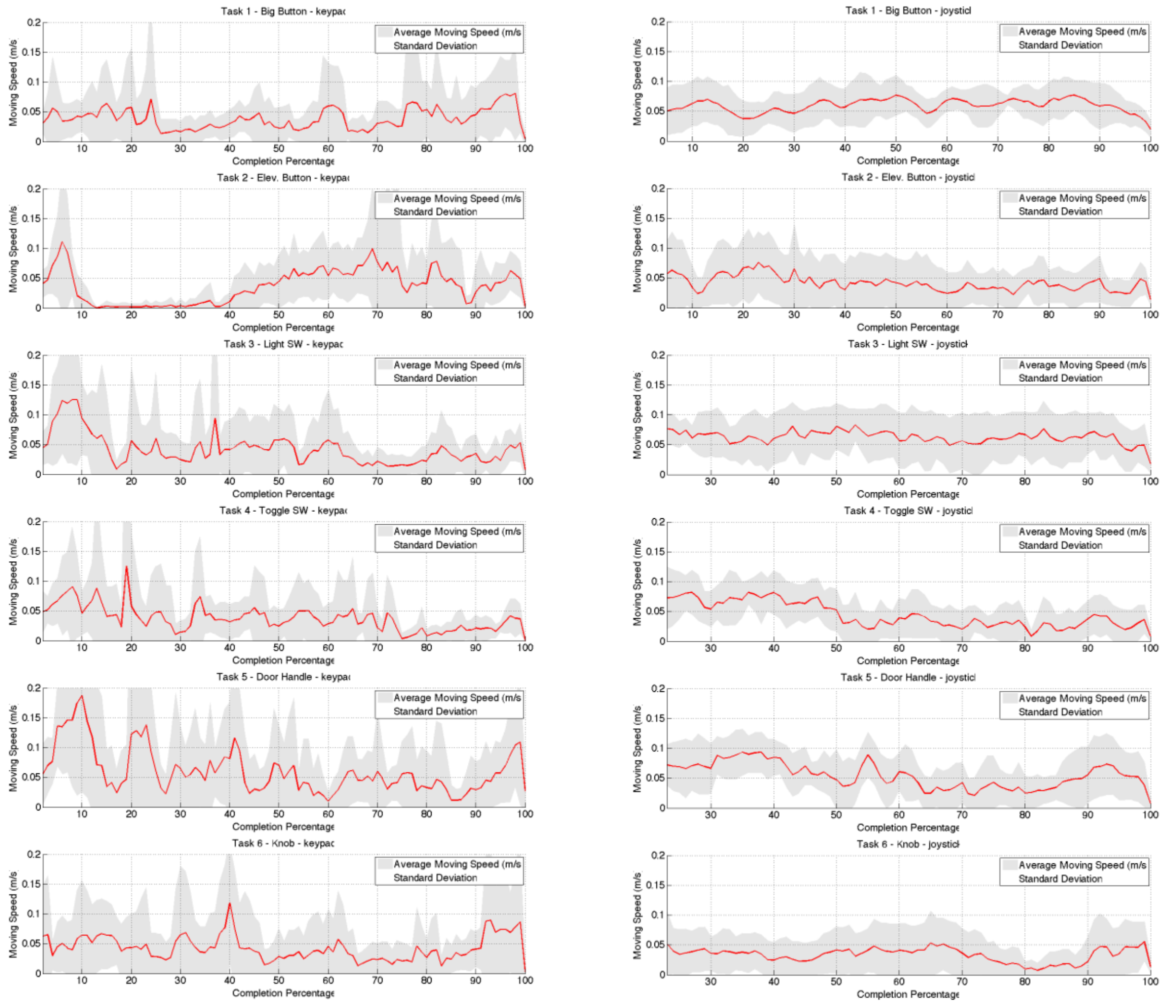

Figure 16. The moving speed of the fastest 10 trials of the case participants (left: keypad, right: joystick).

Figure 15 and Figure 16 shows the moving speed on the normalized trajectories of the fastest ten trials in control and case group. The trajectory was normalized by the task completion time as completion percentage. The moving speed is computed as the vector length of the XYZ velocities at each time period. These figures help us to see the moving speed changing characteristics while moving in the open space and approaching the target. The red curve shows the average of the ten trials and the gray area shows the standard deviation.

In the control group, the joystick showed less variation in the moving speed during moving. When using the keypad, we can see a significant speed drop in the 20-30% and 60-80% in the keypad, where most users stopped or slowed down. The Knob task showed differently than the others, where it slowed down at 50-60% for finer adjustment for grasping and turning. In contrast, the joystick did not show a significant speed drop at the beginning of most tasks. Participants maintained a steady speed after start until approaching the target. In the Big Button using the joystick, there was one speed drop at 20% of the completion where the participants switched from vertical movement to horizontal movement. The users started to slow down at 70-90% in the Elevator Button and Light Switch tasks. In the Toggle Switch and Door Handle tasks, participants decelerated about half of the speed at 50-60% for finer adjustment the approaching to the target. In the Knob task, participants operated at lower speeds for more than half of the completion time.

In the case group, similar characteristic of larger standard deviation was also found in the keypad trials. Most speed reduction occurs at the similar percentage as the control group, 20-30% and 60-80%. However, interestingly, in the Elevator Button task by the keypad, it seems almost all participants in the ten trials stopped at the same time at 13% for about 10% long of completion time. On the contrary, the joystick showed less dramatic speed change. Case participants maintained the speed around 0.05-0.1 m/s on average for moving in the air and approaching. However, control participants moved up to 0.1-0.15 m/s when moving in the air and 0.05-0.1 m/s when approaching the target. Unlike the control participants in the Knob task using the joystick, the case participants maintained with the average speed longer until about 80% and then speeded up for the second movement.

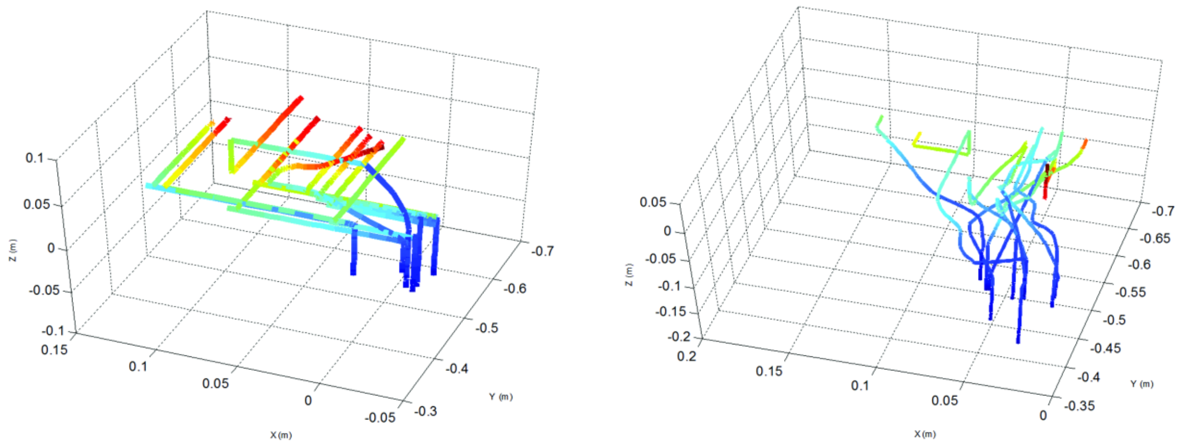

Figure 17. The ARM trajectory of the fastest 10 trials in the big button task using both user interfaces from control group (left: keypad, right: joystick). Trajectories are colored from the dark blue (start position) to the red (finish position).

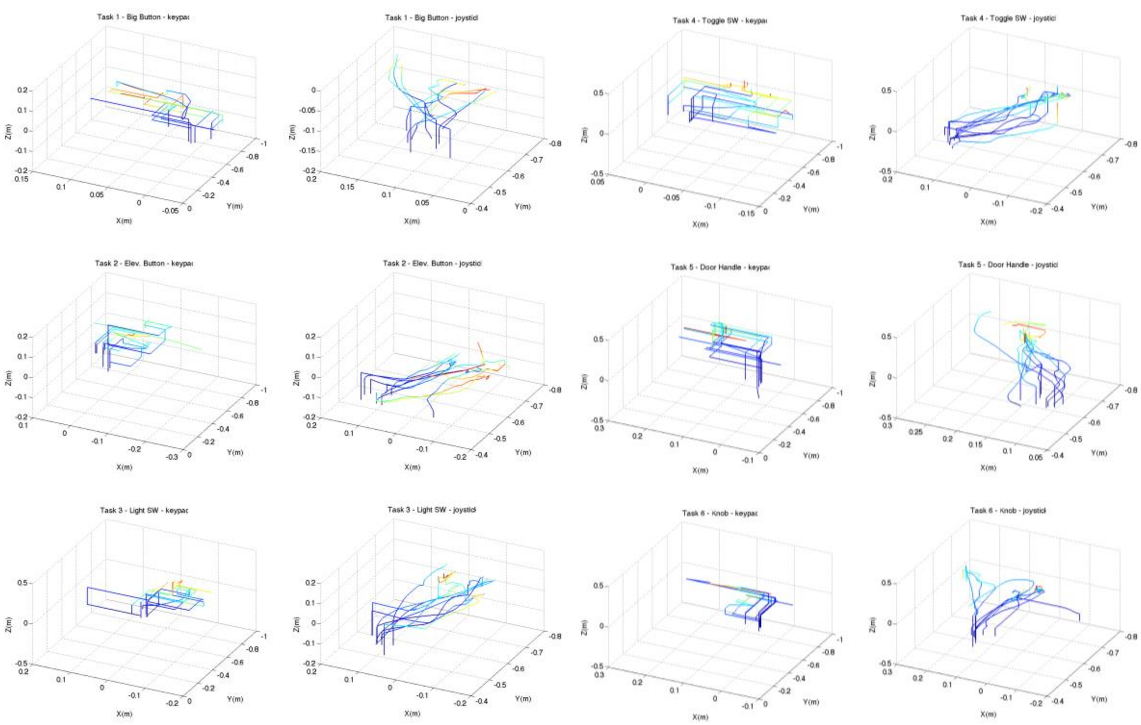

Figure 18. The ARM trajectories of the fastest 10 trials in all tasks from case participants. Trajectories are colored from the dark blue (start position) to the red (finish position).

In order to further examine the motion differences between the two user interfaces, we extracted the fastest ten trails in the Big Button task from the control group and plotted them in Figure 17. This is the easiest task on the ADL task board, which helps to discover how users plan to hit a target. In the trajectory figure, the dark blue indicates the starting location and the red is the end point. The trajectories show that the ARM moves along one axis at a time using a keypad user interface but moves diagonally toward the target using a joystick user interface.

Figure 18 shows the trajectories of the fastest 10 trials from case participants. From the trajectories, we can see that users started to move vertically first because the start location is lower of all targets. After reaching to a certain height, participants using the keypad started to move either left/right or forward, but more diagonal curves if using the joystick. Similar to the trajectory behavior found in the control group, case participants tended to move one axis at a time while using the keypad and move diagonally when using the joystick. In both user interfaces, the majority of the excess left and right movements were caused by the overshoot error that the user moved too fast to miss the target. This trajectory pattern difference suggested that the joystick is easier for the first-time users to perform more optimal trajectories.

4.4.3 Cognitive Workload

Although there were statistical differences in the task completion time and throughput between keypad and joystick, we did not find statistical differences in the NASA-TLX and weighted workload (Table 9). However, Figure 19 indicates that both user interfaces show similar perceived loading distribution in the workload subscales. Almost all participants rated lower on the Frustration and Physical Demand and highest on the Mental Demand, Temporal Demand,

and Effort workloads. On the average, the joystick showed lower workload among able-bodied participants but higher among power wheelchair users.

Table 9. NASA-TLX and weighted workload index of two user interfaces (Mean±Standard Deviation)

Perceived Loading		**Control**			**Case**		
User Interfaces		**Keypad**	**Joystick**	**P-value**	**Keypad**	**Joystick**	**P-value**
NASA-TLX		42.2±20.2	38.3±15.8	.532	32.8±18.9	39.6±19.9	.527
Weighted Workload	Mental	12.9±8.6	13.9±8.5	.690	8.7±4.7	11.0±6.0	.453
	Physical	1.5±2.2	2.1±2.6	.460	3.2±3.7	3.6±4.9	.859
	Temporal	9.0±7.8	6.7±6.4	.325	6.7±8.5	9.1±8.7	.607
	Performance	4.3±3.0	5.1±3.9	.474	3.6±3.4	5.0±4.5	.530
	Effort	9.3±6.9	9.3±7.1	.981	6.2±7.2	7.3±5.8	.765
	Frustration	5.2±10.4	1.3±2.3	.123	4.3±6.6	3.6±5.7	.817

* Significant after Bonferonni adjustment ($\alpha = 0.05$)

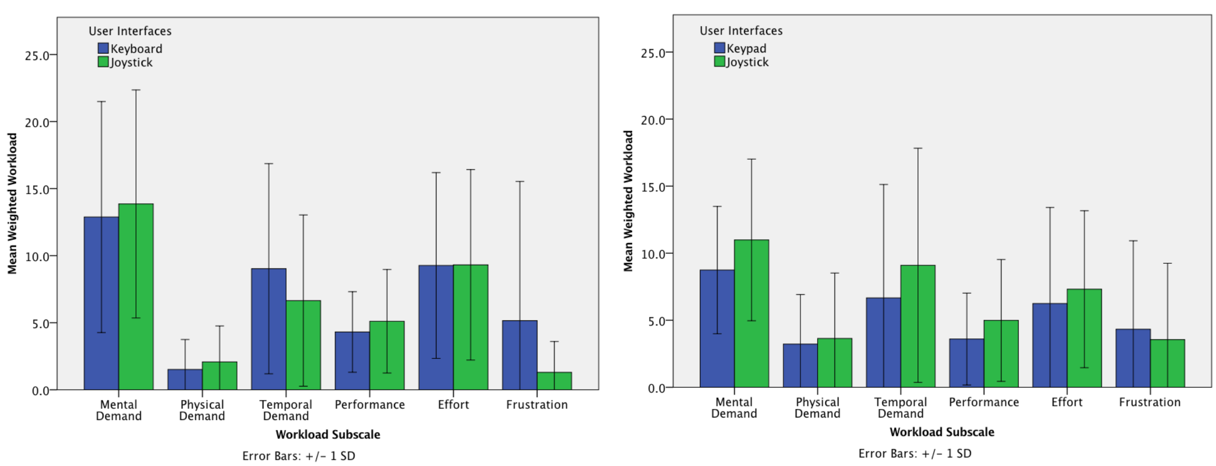

Figure 19. Weighted workload scores of two user interfaces among able-bodied participants (left) and power wheelchair users (right)

4.4.4 Questionnaire and Interview

4.4.4.1 Control Group

Table 10. Questionnaire items interviewed before and after the practice and testing of each user interface by the control group (Mean±Standard Deviation)

Interview Question	Keypad			Joystick		
	Pre	Post	P-value	Pre	Post	P-value
1. Learning to use ARM will be/was easy for me	4.85±2.72	7.00±2.47	.003*	7.55±1.91	6.37±3.17	.065
2. It will be/was easy to get ARM to do what I want it to do	5.55±2.74	6.95±2.44	.072*	7.50±1.24	6.47±2.44	.064
3. I am anxious about using ARM	5.05±2.84	4.40±3.00	.382	4.75±2.79	4.60±3.03	.836
4. It will be/is confusing for me to use ARM correctly	5.00±2.29	3.65±2.83	.041*	4.75±2.55	5.05±3.46	.744
5. It would be easier to just get another person to help rather than using ARM	5.55±2.86	4.90±3.14	.222	5.25±2.86	4.32±3.11	.245
6. ARM is attractive from a physical standpoint	5.30±2.01	4.80±1.99	.248	6.35±2.96	5.90±3.02	.529
7. It will/would be embarrassing to be seen using ARM	2.90±1.65	3.00±2.08	.781	4.15±2.58	2.35±1.84	.007*

* Significant after Bonferonni adjustment (α = 0.05)

Table 10 shows the response of the user interfaces comparison before and after using the ARMs. We found statistically higher in the ease at learning, usage, and lower confusion in usage with the keypad user interface (Item 1, 2, and 4). However, participants felt statistically less embarrassing (Item 7) after using the joystick user interface. Both user interfaces have similar ratings among these nine pre-post items. Participants reported being less anxious and embarrassed about using the user interfaces and ARMs.

Table 11 shows the difference in interview items between the two user interfaces. There was no statistical difference found except one item (Item 9). Statistically higher rating was found in the working improperly item (Item 9).

Table 11. Questionnaire items interviewed after completion of ADL task board testing with each user interface by the control group (Mean±Standard Deviation)

Interview Question	Keypad	Joystick	P-value
8. The benefits ARM will provide are worth the cost of the device	5.45±2.28	4.80±2.17	.213
9. ARM sometimes doesn't work properly	4.40±3.00	2.80±1.91	.049*
10. ARM seems too flimsy, like it might break	3.60±2.33	3.90±2.55	.700
11. If ARM needs repairs, I could probably fix it myself	2.80±2.38	3.20±2.95	.631
12. ARM is just as good as newer things on the market	5.74±2.51	6.40±2.39	.366

* Significant after Bonferonni adjustment ($\alpha = 0.05$)

4.4.4.2 Case Group

Table 12 shows the users attitude before and after using the ARM user interfaces. No statistical difference was found in both user interfaces. Both user interfaces have similar ratings among these nine pre-post items. Case participants reported positive with the Item 5 and 6.

Table 12. . Questionnaire items interviewed before and after the practice and testing of each user interface by the case group (Mean±Standard Deviation)

Interview Question		**Keypad**			**Joystick**	
	Pre	Post	P-value	Pre	Post	P-value
1. Learning to use ARM will be/was easy for me	6.20±2.86	6.00±2.67	.873	6.70±2.63	7.10±2.51	.732
2. It will be/was easy to get ARM to do what I want it to do	6.00±2.40	5.60±2.68	.729	6.90±2.60	7.20±2.20	.784
3. I am anxious about using ARM	4.40±2.59	3.90±1.91	.629	4.00±3.13	3.67±3.00	.816
4. It will be/is confusing for me to use ARM correctly	5.00±1.94	5.00±2.62	.999	4.10±2.13	3.90±2.42	.847
5. Using an ARM will /would make my life easier	7.10±1.97	7.20±2.70	.926	7.80±1.40	8.20±1.23	.506
6. Using an ARM will/would help me to achieve important goals	6.90±1.66	7.10±2.42	.832	7.20±2.66	7.90±1.37	.469
7. It would be easier to just get another person to help rather than using ARM	5.40±2.17	5.30±2.21	.920	4.20±2.86	4.80±3.11	.659
8. ARM is attractive from a physical standpoint	6.40±1.43	7.00±1.65	.409	6.10±2.81	6.60±2.88	.699
9. It will/would be embarrassing to be seen using ARM	4.50±2.50	4.70±2.35	.856	3.11±1.90	4.20±2.94	.357

* Significant after Bonferonni adjustment (α = 0.05)

Table 13 shows the difference in interview items between the two user interfaces. There was no statistical difference found in these interview questions. Case participants reported that they prefer control the ARM independently rather than either assistance (Item 15) or total control

(Item 17) from a remote caregiver. Case participants also moderately agree that the benefits ARM provides are worth the cost.

Table 13. . Questionnaire items interviewed after completion of ADL task board testing with each user interface by the case group (Mean±Standard Deviation)

Interview Question	Keypad	Joystick	P-value
10. The benefits ARM will provide are worth the cost of the device	7.60±1.84	6.00±1.83	.067
11. ARM sometimes doesn't work properly	4.30±2.95	3.40±2.53	.471
12. ARM seems too flimsy, like it might break	3.80±2.49	3.30±2.54	.662
13. If ARM needs repairs, I could probably fix it myself	2.10±1.85	1.90±1.85	.812
14. ARM is just as good as newer things on the market	5.70±2.79	7.40±2.46	.166
15. I would prefer that a caregiver assist me in operating ARM remotely	3.20±2.86	2.80±2.90	.760
16. I would prefer to operate ARM independently	8.30±2.00	7.80±3.71	.712
17. I would prefer that a caregiver operate ARM for me remotely	2.30±2.06	1.50±0.97	.281

* Significant after Bonferonni adjustment ($\alpha = 0.05$)

In the open interview, tasks that participants would like to do with ARM are “everything including cooking, cleaning, dressing,” “wash clothes, help with eating, changing bulbs, and vocational activities.” The participants liked the “long reach, capability to reach and grasp, easy to use, and providing independence.” The items that participants liked least were the cost and size. What the participants would do differently if redesigning the ARM is to “allow it to lift more weight, more flexible user interfaces, and four fingers.” The places they would not be willing to use ARM in quiet places like a church or library.

4.4.5 WMFT-ARM

Table 14. Average completion time of WMFT-ARM

Task Item	Joystick		Keyboard		p-value		Cohen's d	
	Completion Time	Functional Ability	Completion Time	Functional Ability	Completion Time	Functional Ability	Completion Time	Functional Ability
1	12.47±9.48	4.8±0.42	21.46±10.91	4.5±0.85	.065	.331	.879	-.447
2	11.19±6.23	4.9±0.32	25.60±19.01	4.6±0.84	.035*	.306	1.019	-.471
3	30.75±37.32	4.5±0.71	50.18±37.32	4.3±1.16	.161	.647	.653	-.208
4	31.53±19.22	4.5±0.85	88.68±61.00	3.8±1.23	.011*	.156	1.264	-.662
5	71.84±53.84	3.8±1.03	109.41±112.77	3.7±1.34	.354	.854	.425	-.083
6	204.42±173.85	3.1±1.79	85.19±90.75	4.0±1.15	.071	.198	-.860	.597
7	73.87±96.9.	4.2±1.75	55.94±38.33	3.7±1.57	.604	.430	-.243	-.314
8	55.08±36.85	4.6±2.00	156.92±55.08	3.9±1.20	.108	.131	.847	-.439

* Significant after Bonferonni adjustment ($\alpha = 0.05$)

Table 14 and Figure 20 show the completion time of each task item in the WMFT-ARM version. The average task completion time of the joystick user interface was smaller in most of the tasks. However, in task 6 (pick up key), the keyboard performed faster on average than the joystick. This might be because users spent more time in switching back and forth between translation and rotation modes to adjust the appropriate hand position for picking up the key. All participants finished all the task items. Some participants required verbal cues to complete difficult tasks. Both user interfaces showed very high functional ability score in simple tasks and the relatively low score in the difficult tasks. Statistical differences were found in the item 2 – hand to box and

4 – lift can to mouth. The joystick interface is statistically faster in these two tasks. We found that the joystick user interface performed slower on the item 6 – lift key and 7 – turn key in lock.

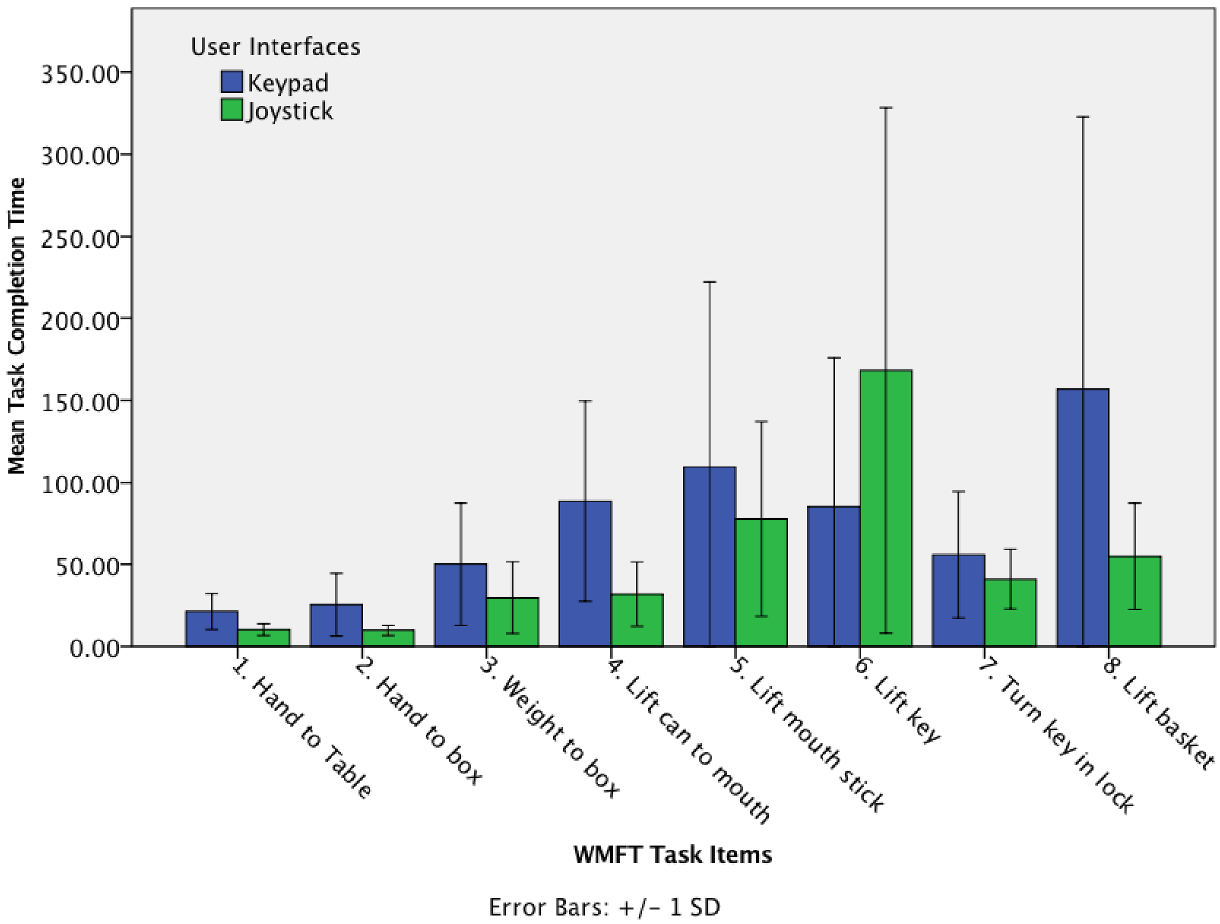

Figure 20. The task completion time of each WMFT-ARM task item

4.4.6 Validity of the ADL Task Board

The validity was examined by the correlations between the ADL task board performance and WMFT-ARM test results. All tasks in the ADL task board showed statistically higher correlation (Table 15) with item 2-5 in WMFT-ARM. Item 8 – lift basket also demonstrated higher correlation to the Big Button task. The item 6 and 7 showed relatively lower correlation with the ADL task board tasks. Overall, the ADL task board demonstrate moderate to high correlation to the WMFT-ARM test.

Table 15. Correlation between ADL task board and WMFT-ARM

	1. Hand to Table	2. Hand to Box	3 Weight to Box	4. Lift Can to Mouth	5.Lift Mouth Stick	6. Lift Key	7. Turn Key in Lock	8. Lift Basket
Big Button	.410	.763**	.725**	.846**	.649**	-.064	.190	.632**
Elevator Button	.213	.854**	.727**	.813**	.645**	.169	.058	.084
Light Switch	.148	.874**	.784**	.808**	.678**	.080	.001	.010
Toggle Switch	.242	.819**	.731**	.867**	.650**	.017	.029	.270
Door Handel	.295	.862**	.843**	.778**	.712**	.032	.039	.232
Knob	.212	.852**	.856**	.828**	.764**	.106	.091	.354

** p<0.001

During the testing, we noticed that when using the keyboard user interface, for the first several tasks, the users frequently visually verify the symbols on the keyboard and moving of the ARM. However, the frequency of visual verification was reduced in the later tasks. This phenomenon indicates that users have memorized the key's location and built up the motor automaticity. In the first four tasks, most users only used translation motion to complete the task. In the item 5 and 6, mode switching between translation and rotation slows the joystick interface. However, in task item 7, with a single rotation, the proportional control of the joystick interface can accelerate the ARM to the desired rotational speed faster.

4.4.7 Sensitivity / Responsiveness to User Interface Change

Table 16. Sensitivity/Responsiveness to change of the ADL task board and WMFT-ARM of the case group

ADL Task Board	Cohen's d Average in 3 Trials	Cohen's d Fastest Trial
Big button	1.249	1.085
Elevator button	1.040	.910
Light switch	1.007	1.034
Toggle switch	1.143	.955
Door handle	.834	1.054
Turning knob	.846	.930

WMFT-ARM	
1. Hand to table	.879
2. Hand to box	1.019
3. Weight to box	.653
4. Lift can to mouth	1.264
5. Lift mouth stick	.425
6. Lift key	-.860
7. Turn key in lock	-.243
8. Lift basket	.847

Responsiveness to change, also called sensitivity, is the capability of a test to detect clinical changes either from the intervention or the progress. It is measured by effect size, Cohen's d. The effect size is computed as mean change divided by the standard deviation of the mean at baseline. Here, the main difference in the ADL task board and WMFT-ARM testing is the ARM user interfaces. Statistically, the larger difference between UIs or smaller standard deviation would result in larger Cohen's d, which leads to higher sensitivity. By taking keypad user interface as the baseline, the sensitivity to the user interface change can be computed. The ADL

Task board shows higher responsiveness to change with effect size 0.8-1.2 (Table 16). The WMFT-ARM shows relatively less responsive to change in item 3, 5, and 7. The results suggest that the ADL task board is more capable to detect difference in user interfaces in comparison with the WMFT-ARM.

4.5 DISCUSSION

This is the first study comparing commercially available ARMs' original user interfaces with standardized ADL tasks. The study also investigated the performance evaluation and self-reported workload and impressions. One of the goals of this study was to evaluate the ARM performance on standardized ADL tasks with two user interfaces. The second goal of this study was to evaluate the user perceived workload and perspectives for improvements.

4.5.1 Difference between ARM User Interfaces

One of the differences between the two user interfaces is the incremental speed control in the keypad user interface and the proportional control in the joystick user interface. While using the keypad user interface, some participants tried to keep pressing or holding down the key to speed up the ARM motion, but sometimes overshot the target. Consequently, more time was spent on correcting from an overshoot error. In the joystick user interface testing, participants accelerated when the ARM was moving in opened space and smoothly slowed down when approaching the target to prevent overshoot, which is a similar reaction to using pointing devices [42]. The moving speed of the fastest ten trials (Figure 15 and Figure 16) showed that the participants using joystick are more capable in maintaining steady speed when moving in the opened space or in the vicinity of the target. However, instead of using a proportional speed control on the joystick, it was noted that some participants used the joystick as bang-bang controller to make small movements by quickly pushing the joystick knob to its extreme boundary and then releasing it immediately. This observation from testing suggests that training on the familiarity with speed control on both UIs may improve the performance by reducing overshooting and producing accurate fine movements.

Mode switching is another difference between the two UIs. The keypad user interface has all the translational, rotational, and grasping function keys within one keypad for users to easily access. The original 4x4 keypad provides joint and Cartesian control mode. Participants preferred to use Cartesian control mode most. The joystick user interface, default set as Cartesian motion, has to switch modes between the translation, rotation, and gripper modes. Participants spent most of the time in the translation mode. It is worth noting that there were two different techniques used with the Door Handle and Knob. Most participants used wrist rotation mode in the Door Handle and Knob for both UIs, but we observed some participants completed these tasks with translation mode only. Door Handle can be completed either using only translation mode or with a combination of translation and rotation. During the testing, some participants switched between translation and rotation modes in the first or second trial and only used translational mode in the third trial to complete the task faster. The Knob task requires more accurate alignment with the knob rotation axis for better grasping and wrist spinning motion. The majority of participants first moved to the proximity of the knob, then rotate the wrist to align with the turning axis, moved forward and grasped the knob, and finally spun to the target angle. This complicated series of motion results in statistically higher pauses frequencies and times for switching modes and re-planning in alignment. However, we found a few participants successfully completed the Knob task by using only translational mode. The technique utilized sliding the ARM fingers on the edge of the knob a few times. Therefore, although the Door Handle and Knob tasks are rotational motion tasks, performance may be improved by incorporating different techniques by reducing mode switching.

Affordability in managing multiple axis movement is the other difference. As shown in the trajectories of the best ten trials of the light switch task (Figure 17), we can clearly see two types of maneuvering techniques: multiple axis and single axis. The multiple axis was when the joystick user controls the ARM to move directly toward the target. Conversely, the keypad user interface moves the ARM one axis at a time. Although the keypad user interface has the capability to maneuver the ARM with more than one axis simultaneously by pressing more than one key. We observed that some participants tried to apply this technique in completing an ADL task. However, it was difficult to accurately guide the ARM toward the target with incremental speed control; and consequently, the user had to stop and go back to single axis control. These findings suggest that better performance can be improved by shortening the movement trajectory. Conversely, the findings also suggest that the training with a keypad user interface can start with single axis control.

For the clinical application in prescribing ARM UIs, the lower roughness and higher throughput in the joystick UI suggested that joystick UI may be more efficient for most users that can operate both UIs even with two-axis joystick. However, for people with less hand and arm functions, the keypad may be the only UI option. Training would significantly help in adapting to the keypad UI.

4.5.2 Comparison between Performance Tests

The ADL task board shows moderate to high correlation to WMFT-ARM, which is adapted from a clinical accepted assessment, WMFT. The large correlation in the tasks with basic ARM action, pick and place, and drinking, suggested that better performance on the ADL task board would result in better performance on the WMFT-ARM. This result suggests that ADL tasks are capable of measuring the ARM user interface and its usage in ADLs.

The higher effect size in the ADL task board results shows that it is more sensitive to the changes between user interfaces. This is probably because the ADL task board included more restricted starting and target location in conjunction with the electronic switches and potentiometers, which may reduce the variability in determining task completion. In addition, restricted starting and target positions limited the strategies and space that participants can use and plan to complete the task. On the contrary, the WMFT-ARM task items consist less restricted starting and ending position. Participants may perform with different trajectories. Even though the excellent intra-rater reliability showed the rater is highly reliable on the same day or different day, the individual variation in task completion strategies reflects more on the WMFT-ARM.

Overall, the validity and sensitivity tests revealed that the ADL task board performance evaluation demonstrate similar outcome measurements for the ARM user interfaces. In consideration of the training and repeated reliability tests in most clinical tests, the ADL task board may be an easier and quicker solution for ARM user interface performance evaluation.

A ceiling effect is one of common phenomenon in the functional assessments used by occupational therapists. A type of ceiling effect is that the difference of independent variable, such as user interfaces in our study, is no longer detected by the dependent variable, such as throughput or task completion time. For example, obviously, there is a ceiling effect in the functional ability score of the WMFT-ARM because if users can perform all tasks using two user interfaces normally and without any error, they will all get full score, which means that the difference between user interfaces has no effect on the functional ability score. This is not a bad thing because this case implies that users can perform ADL tasks independently and fluently. For most occupational therapy tests such as QuickDASH used in this study or Barthel Index [52], ceiling effect is possible between the healthy participants. However, timed tasks would significantly reduce this type of ceiling effect [53] because there are always rooms for improvement. In one ideal scenario, if recruited users are so experienced using both keypad and joystick interfaces that there is no difference found in their performance on the ADL task board or WMFT-ARM. This scenario leads to the second type of ceiling effect, which is that above some level of variance in the independent variable, like the experienced users in this case, cannot be easily measured. The solution is to provide various means for measurement, for example, using more difficult tasks on the ADL task board to test the limit of these experienced users' performance. Thus, to alleviate the second type of ceiling effect, a further improvement of the ADL task board is to develop interchangeable task modules with various difficulties, which will be discussed in Chapter 6.

4.5.3 Cognitive Loading and Users' Feedback

Even though performance was different between both UIs, there was no statistical difference found in the cognitive loading and user's impression in both control and case groups. Although the joystick user interface shows lower average NASA-TLX score, the variation between participants did not yield a statistical difference. It is worth noting that the weighted workload shows that participants felt low frustration and physical loading with both UIs, but struggled most with mental effort workloads. These results reveal that while maneuvering the ARM, it requires a significant amount of loading in calculating, planning, looking, and searching. However, low frustration and physical loading indicate that it was not physically difficult to maneuver the ARM to the target. These results suggest that the difficulty in the ARM user interface is to make a feasible trajectory plan and translate the plan into keystrokes or joystick movements.

The questionnaire reveals that participants viewed these two UIs as easy to learn and use. Participants in the control group rated the keypad user interface as easier and less confusing after the training and testing. There was no statistical difference found in the case group. This may suggest that the keypad user interface may look more complicated at first for the able-bodied participants. However, after practicing and testing with the task board, the participants perceived the keypad as easier and less confusing. These results suggest that the amount of time in training and practicing is essential for a keypad user interface. With sufficient time in training, the users' perception to ease was increased. In the overall opinion questions, most participants had positive responses to the ARMs and UIs. The participants' preference was toward more on the independent control with the keypad and joystick user interface rather than controlled by a remote caregiver. In the open interview questions, participants reported that they liked most was "efficiency, smoothness, easiness to use, independence, reach, attractiveness." What they like least was "fragility, mobility, cost, and fear in hurting objects or myself." What the participants would like to change were "force sensing fingers, stop operation on an impact, reducing flipping modes, doing heavy duty tasks (>10kg), more safety protection, spinning joystick to open/close fingers, more joints, and more accurate control." During the testing, three participants expressed that their experiences in video games for years helped to learn the UIs. This suggests that gaming experience may be a factor in learning UIs, which should be considered in the future studies.

4.5.4 Study Limitation

This study has limitations. First, the participants were all first time users with limited experience in the ARM user interfaces. Therefore the performance may vary among trials. However, this helps to discover the major barriers to first time users and shows the norm data of inexperienced users. Second, both control and case groups were able to complete the tasks on the ADL task board and WMFT-ARM. However, the NASA-TLX weighted scores suggested that these are relatively easier tasks, which are categorized as simple tasks in the ICF. For the complex sequential tasks or very small objects such as earrings, it is difficult to test manipulation because strategies may be different between users. Third, although the training for ARM UIs followed the testing procedure from basic to simple movements and most participants finished training as scheduled of thirty minutes, some participants finished training earlier than planned procedure and requested to start the testing, but some required more time to get familiar with the UIs due to individual variability in learning abilities and motor control. Both situations did not show significant correlation with the ARM performance. Therefore, the training time was partially affected by the confidence level of the participants. However, the normative data collected in this study could be an indicator of training efficacy for future studies. One example for the future can be that the participants keep practicing until the performance reaches the normative data on the ADL task board or WMFT-ARM so that every participant starts the testing with similar basis in ARM control. Forth, the pilot study was designed to evaluate ARM performance among the general population. The correlation between performance and individual variation factors, such as gaming experiences, motor skills, spatial skills, and vision/perception, were not considered in this study. The gaming experiences became one of important factors in the human robot interaction, even in the health or surgical robot [54]. The motor skill is one important indicator of the physical capability in operating manual user interface. In this study, we only recruited people have no difficulty using the keyboard and joystick, which filtered out users with weak motor skill. The spatial skill and perception is another essential factor that may affect performance. Studies [55], [56] showed that people with higher spatial skill performed task statistically faster. However, there was no study found in the people with disabilities. Therefore, these factors may be included in the future studies to examine the correlation to the ARM performance.

For the future work, improvement of interchangeable tasks will help in the evaluation of complex and sequential tasks or tasks with small objects. Third, we only evaluated the commercial UIs used for the ARMs to establish the norm data of ARM performance for future comparison. Some developing UIs such as brain-computer interface (BCI) will be evaluated in the future studies. Forth, although we observed differences in the questionnaire items between control and case groups, we were not able to conclude that the difference was affected by the group differences because the reliability and validity of the questionnaire was not well established. However, with the with-in subject comparison, we could perceive the increased easiness and reduced confusion in the keypad UI for the control group.

4.6 CONCLUSION

As the needs for ADL assistance are increasing among people with upper extremity impairment and the older adults, assistive robotic manipulators (ARMs) have shown enhanced assistance and increased independence in completing ADL tasks. This study introduces environment-independent performance evaluation outcome measurements: throughput and roughness. Two commercial ARMs were evaluated with their original user interfaces; joystick and keypad. The results provide preliminary evidence for the performance differences between commercial ARM user interfaces. We also discussed barriers and recommendations for training and evaluation for first time users. The results may help clinicians to develop appropriate training and guide researchers to develop ARM UIs to better-fit users' needs.

5.0 ADVANCED ARM USER INTERFACE

In this chapter, we will answer the second question of the ARM user interfaces: can we make them better? What we mean "better" is completing a task easier and with fewer pauses. We will first describe the challenges in applying sliding-autonomy interfaces and the development of autonomy and sliding-autonomy. We will then introduce the platform that can achieve both manual and sliding autonomy, the Personal Mobility and Manipulation Appliance (PerMMA) system. We will show the results with improved task completion time and reduced error in three levels of ADL tasks: single action, multiple actions, and sequential tasks to demonstrate the effectiveness of the PerMMA system.

5.1 CHALLENGES IN SLIDING-AUTONOMY INTERFACES

From the aforementioned literature review [40], implementing autonomy on ARMs can dramatically reduce the time in completing simple activities such as pick-and-place tasks [7], [57] in comparison with direct joint or Cartesian control manually. In addition, sliding-autonomy opens up a way that users can involve and correct the robot motion if autonomous function is not applicable or path planning has failed [58], [59]. In this way, an ARM can perform more complicated activities with a series of subtasks with a user's guide. There are still barriers to applying a sliding-autonomy interface for power wheelchair users' daily environments such as home, office, or community.

The first is the size of an add-on user interface. The sliding-autonomy interfaces installed on a wheelchair cannot increase the footprint of the wheelchair in order to drive through narrow hallways and doors [30]. In addition, although mounting a large sized screen can provide abundant visual feedback, it may occlude the user's field of view during navigation and manipulation.

The second is the physical input interface. There are limited studies involving including sliding-autonomy using the current ARM direct input interface – joystick and keypad. A user interface should to allow the user to focus more on the tasks to be performed instead of how to control the robot [39]. For example, the focus on eating and drinking tasks should be the pleasure of the food and drink instead of how to convey the food or drink to the user's mouth. Implementing autonomy in the robotic system minimizes human loading in completing complicated tasks like picking up a drink [57]. Including sliding-autonomy using the same direct control interface may reduce learning and confusion.

The third is the level of assistance. When completing a complicated activity with a series of tasks, it is important to provide different levels of assistance based on the complexities and the status of the task. For example, the user may just need to accelerate the speed along the trajectory while moving the ARM in an open space and control manually while approaching the object. Various options with different levels of assistance provide users the flexibility to select the optimizing interface depends on the types of disabilities and environments.

5.2 DEVELOPMENT OF ARM USER INTERFACES, AUTONOMY, AND SLIDING-AUTONOMY

The manual control interfaces of current commercially available ARMs such as a joystick or keypad allow powered wheelchair users to move a robot either joint by joint or within a Cartesian coordinate system [40]. Instead of being only controlled by the wheelchair user with single ARM, the PerMMA robot is composed of two moveable ARM mounted on a track system located around the wheelchair seat so that the manipulators can slide to the back of the wheelchair while driving through a narrow hallway or door. Three user interfaces were developed: local user, remote user, and cooperative control. The local user method allows the wheelchair user to control PerMMA through a touchpad [60]. A remote user control method transmits the authority of ARM control to a remote operator, who could be a caregiver or family member of the wheelchair user. In this way, caregivers can remotely complete ADL through the visual feedback from the cameras on the robot's shoulders. Cooperative methods take advantage of better perception from the local wheelchair user and dexterity from the remote operator. A previous focus group study revealed that users prefer to control PerMMA by themselves [61]. The PerMMA established a framework of sharing the ARM control to another person with more dexterity. Our approach extends this concept to include autonomy into the system with different levels of interaction both for a local and remote user.

Fully autonomous function eases the frustration and reduces the time when completing ADL tasks. Tsui et al. [7] developed a touchscreen interface for ARM. This interface allows the user to select an object on the touch screen using the image captured by the stereo camera above the wheelchair. After the object is selected, the robot then moves to the selected location and adjusts the gripper pose to grasp the object through another stereo camera in the gripper. This dramatically simplified the user's input to a single click and reduced cognitive loading from complicated joint-by-joint control. It helps users with lower cognition to complete the pickup task easily. In addition, Chung et al. [57] developed autonomous functions for drinking. Our approach develops an alternative method provided for users to correct the movement if there is an error in the detection or robot position feedback.

While performing more complex tasks with a series of actions, an appropriate manual correction method is necessary to ensure task completion. Chen et al. [58] developed a graphical control interface for the PR2 robot to provide users both autonomous actions and direct manual control when the autonomous functions are not applicable or failed. A head tracker is used for moving the cursor on screen. This sliding-autonomy graphical user interface includes point-and-click reaching and an interactive manipulation interface to help the user to remotely complete ADL such as fetching a towel from the kitchen. The user interface allows the user either supervising the autonomous function or making target pose adjustment. The lesson they learned is that this manual control interface is useful when there is no suitable autonomous tool or there is an error from sensors. This system involves human and abundant knowledge of manipulation and the surrounding environment as an expert system in solving problems when the robot failed to complete the task.

Dragan et al. [59] developed a shared teleoperation method for assistive robots – HERB through a Kinect posture sensor. They introduced policy blending formalism that seamlessly merges manipulation knowledge both from the human and path planning algorithms. The advantage in this formalism is that when the object prediction is not accurate, the grasping movement can still be corrected by the human in the loop. Our approach extends this idea to provide various levels of interaction with the ARM including degrees of freedom reduction and blending of the manual input.

The Personal Mobility and Manipulation Appliance (PerMMA) by the University of Pittsburgh is the first wheelchair to integrate bimanual manipulation for enhancing the quality of life for people with severe physical impairments [62]. PerMMA utilizes two ARMs on a novel mounting system to enhance its manipulability and mobility [30], [63].

The development work of PerMMA has shown that robot performance effectiveness became a major concern for consumers. The performance is primarily related to the human-machine user interface, which makes the connection from the user's intention to the robot actuation. If the interface is difficult to learn and use, the task performance will not be effective – for example, some tasks, such as eating, require a time limit. The pleasure would be reduced if conveying food from the plate to the user's mouth is so slow that the food becomes cold. Moreover, the user should not need to focus on how to control the robot. Instead, the user only needs to focus on the task on hand. Distributing the cognitive load and robot control between users and controllers became a major research question [39].

5.3 PERMMA SYSTEM DEVELOPMENT

5.3.1 Hardware

The PerMMA system (Figure 21) consists of three main components to control the ARMs: a wheelchair mounted with one or two ARMs, a laptop with object recognition and path planning software, and a local or remote user interface. The ARMs are mounted on a track located around the wheelchair seat so that the manipulators can slide to the back of the chair while driving through a narrow hallway or door. Three methods of the cooperation between local and remote users were developed in a previous study [61]. The local user interface allows the wheelchair user to control PerMMA through a touchpad manually [60]. A remote user interface method transmits the control authority to a remote operator, who could be a caregiver or family member with more dexterous hand and arm function. In this way, caregivers can remotely assist ADL through the visual feedback from the cameras on the wheelchair and control the PerMMA remotely with haptic joysticks. Cooperative methods take advantage of better perception from the local wheelchair user and dexterity from the remote operator. A previous focus group study revealed that users prefer to control PerMMA by themselves [64]. The PerMMA established a framework of sharing the ARM control to a remote operator with more dexterity. Our approach extends this concept to include autonomy and mobile devices into the system for both local and remote users.

The ARM used on the PerMMA system can be an iARM, manufactured by Exact Dynamics (Didam, the Netherlands) or a JACO robotic arm by Kinova (Boisbriand, Quebec, Canada). The ARM is mounted on the side of a powered wheelchair with a camera for object detection (Figure 21). An IEEE-1394 fire-wire camera (Flea 2), manufactured by Point Grey (Richmond, British Columbia, Canada), is mounted with an in-house manufactured holder. A Pentax TV lens with wide field of view (4.8mm 1:1.8) is attached to the camera in order to detect objects within the working space of the ARMs. The ARM and camera are connected to a Lenovo laptop (CPU: 8-core i7-2960XM, RAM: 16GB, GPU: Quadro 1000M, running Ubuntu Linux 10.04) placed under the wheelchair seat.

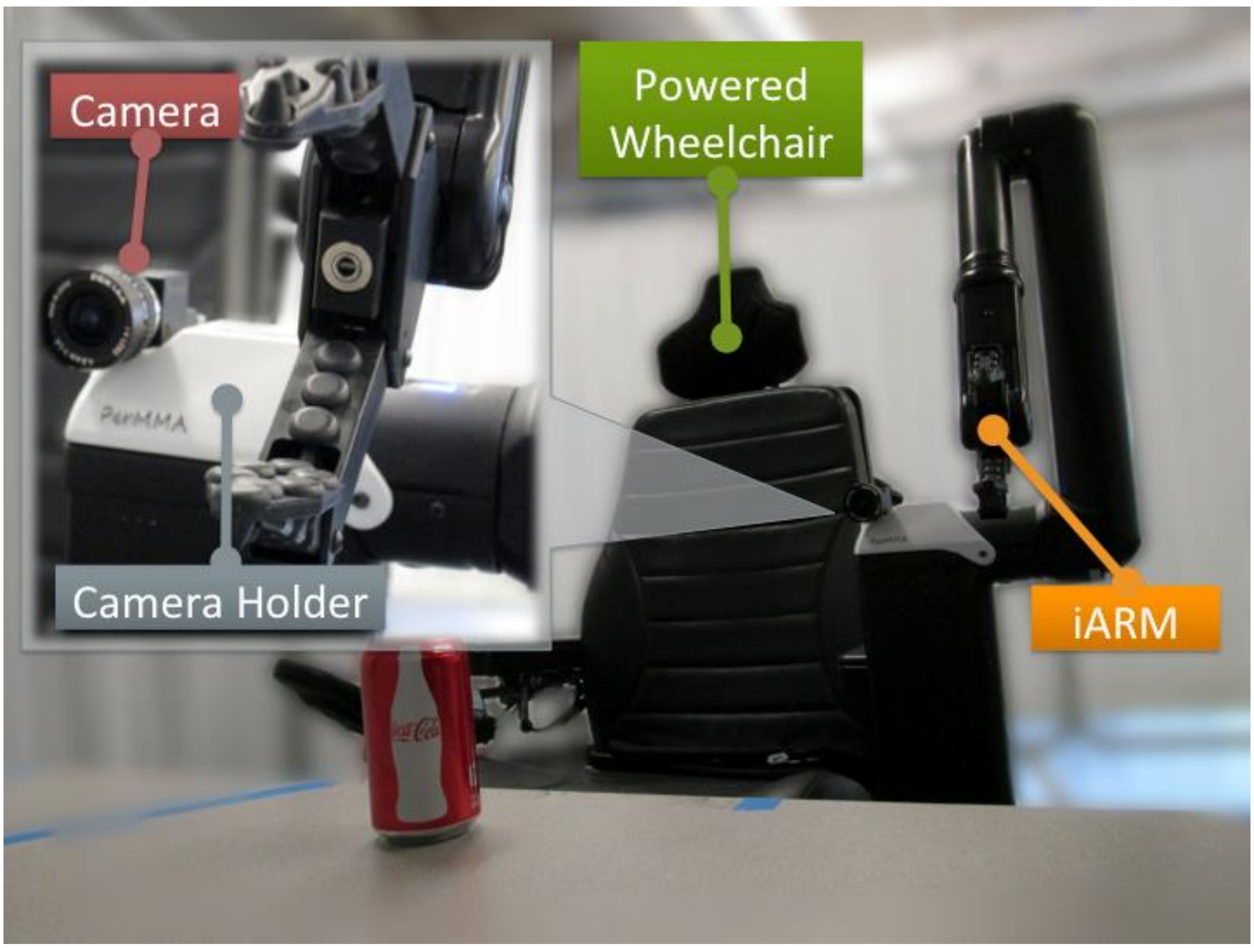

Figure 21. The PerMMA hardware

5.3.2 Software

In order to provide advanced user interfaces including autonomous and sliding-autonomy, we translated HERB's software design [65]. The software can be described as having the following structure: sensing, planning, and performing. The system first recognizes the object's pose and location in the environment. The planning algorithm then searches for an optimized trajectory to pick up the object under the environmental geometries and ARM kinematics with constraints. The trajectory is then performed on the robot to physically retrieve the object.

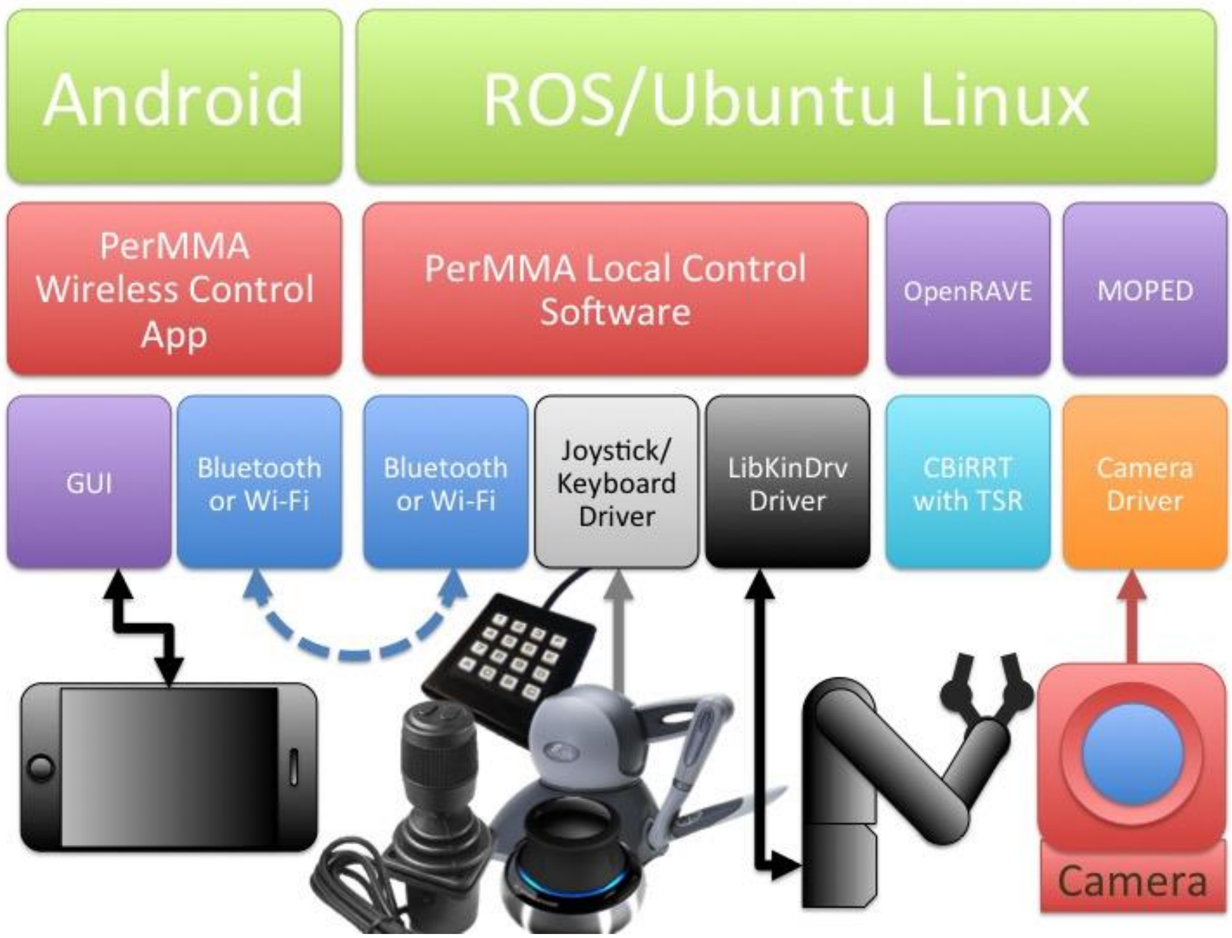

Figure 22. The PerMMA software framework

5.3.2.1 Sensing

The software (Figure 22) has the following functions: object recognition, path planning, and local and remote control user interfaces. The Multiple Object Pose Estimation and Detection (MOPED) algorithm [66] was utilized for detecting multiple objects and estimating their 3D poses and locations using a 640×480 gray scale image. The MOPED algorithm is reliable and robust in detection under complex environments with low latency. The pose and location of the object can be estimated by a single image. The image is first processed by extracting features with Scale-Invariant Feature Transform (SIFT). The extracted features are compared with the stored SIFT features using an offline learning procedure. The matched features are clustered by Iterative Clustering Estimation, which iteratively uses Random Sample Consensus or Levenberg-Marquardt to estimate the object pose hypotheses. These pose estimations are clustered with an implemented object hypothesis scoring function based on M-estimator theory to eliminate the outliers. By taking the advantage of parallel computation of GPU/CPU hybrid architecture, low latency can be achieved [66].

5.3.2.2 Planning

Following the estimation of the pose and location of the objects, the detected object poses are seamlessly placed into the OpenRAVE simulation environment. The OpenRAVE environment conducts path planning and simulates robotic motions, and generates the ARM trajectory. The Constrained Bidirectional Rapid Random Tree (CBiRRT) [67] is a path planner that composes of three components: constraint representation, constraint-satisfaction strategies, and a general planning algorithm. The constraint is represented using Task Space Regions (TSRs). TSRs are task related constraints and can be linked together for complex tasks or end-effector poses such as keeping drink level while moving. In this way, two TSRs are used while bringing the drink to the user. One TSR is to define the acceptable space that the drink will be conveyed to. Another TSR is to keep the drink upright at all times during the movement. The trajectory is then sampled at several waypoints that contain the joint angles and velocities.

5.3.2.3 Performing

The waypoints are sent to the assistive interface to calculate ARM joint position. The driver for the iARM/JACO was also developed to produce joint angular messages and provide robotic movement services via the Robot Operating System (ROS). The communication infrastructure and process of sensing and planning algorithms are managed by the ROS package, which also provides the capability of transferring computational processing between computers.

5.3.2.4 User Interfaces

The local and remote operator can manually control the robot through various options of wired user interfaces such as haptic joysticks, regular joysticks, and keypads. These wired user interfaces could be installed on the wheelchair for local ARM control or connected to another computer for a remote caregiver to teleoperate the PerMMA. An Android based smartphone or tablet can connect to the PerMMA wirelessly via either Bluetooth or Wi-Fi. They can be placed on a lap tray or held on the armrest of the wheelchair for the local user when sitting in the device. With a wireless connection, the ARMs can provide manipulation assistance even when the user is outside of the wheelchair. For example, the user can independently eat breakfast and drink while still in the bed with a nearby PerMMA system instead of getting dressed and transferred to the wheelchair.

The assistive user interfaces developed for the PerMMA provides ARM operation in three different paradigms: manual control, autonomous control, and sliding autonomy control. Each operation modes corresponds to a different level of assistance. The user can manually control the ARMs via aforementioned user interfaces. The ARM can perform the user-defined task autonomously. In addition, in the sliding autonomy, the user and the PerMMA system share the ARM control while performing a task.

The user interface only utilized audio feedback instead of visual feedback such as a computer screen. One main reason is that it is important for the user to visually focus on the ARM autonomous motion. Additionally, while operating the ARM, a computer screen may occlude the user's field of view especially for people with difficulties in adjusting their seating posture. A wheelchair-mounted computer screen with physical input interface used in [7], [58] may enlarge the footprint and if difficult to access buildings with tight hallways or narrow doors. Therefore, the audio feedback not only helps the user to fully concentrate on the task execution but also minimize dimensional modifications to the wheelchair.

5.4 MANUAL USER INTERFACE

5.4.1 Physical User Interfaces

The PerMMA manual user interfaces include two primary commercial physical user interfaces like a 3-axis joystick [16], [28] or a 4x4 keypad [14], [15] allow powered wheelchair users to move the robot either joint by joint or by Cartesian coordinate control. The joystick is simple and efficient, but changing modes and the twisting motion may be difficult or even impossible for some users to manipulate [31]. The keypad is easier for users with difficulties using joysticks, but memorizing key functions and menu hierarchy may be demanding [7]. For a remote operator with dexterous hand and arm functions, the PerMMA can be controlled using haptic joysticks such as Phantom Omni haptic joystick (SensAble Technologies Inc., USA) [64] or a Space navigator (3DConnexion, Boston, MA). These haptic joysticks provide six degree-of-freedom (DOF) motion as ARM velocity or position and two buttons input for gripper opening and closing.

5.4.2 Touchscreen User Interface

5.4.2.1 Development of Touchscreen User Interface

In addition to physical manual user interfaces, a framework that provides customizable touchscreen user interfaces was also developed. This PerMMA control application can mimic the functionality of the joystick and keypad through a touchscreen GUI and has the expendability for autonomous and sliding autonomy robotic functionalities.

The PerMMA touch-joystick user interface matches the capabilities of the joystick but uses a GUI that requires minimal physical exertion using tapping and single-fingered sliding and no difficult motions such as three-finger gestures or two-fingered twisting.

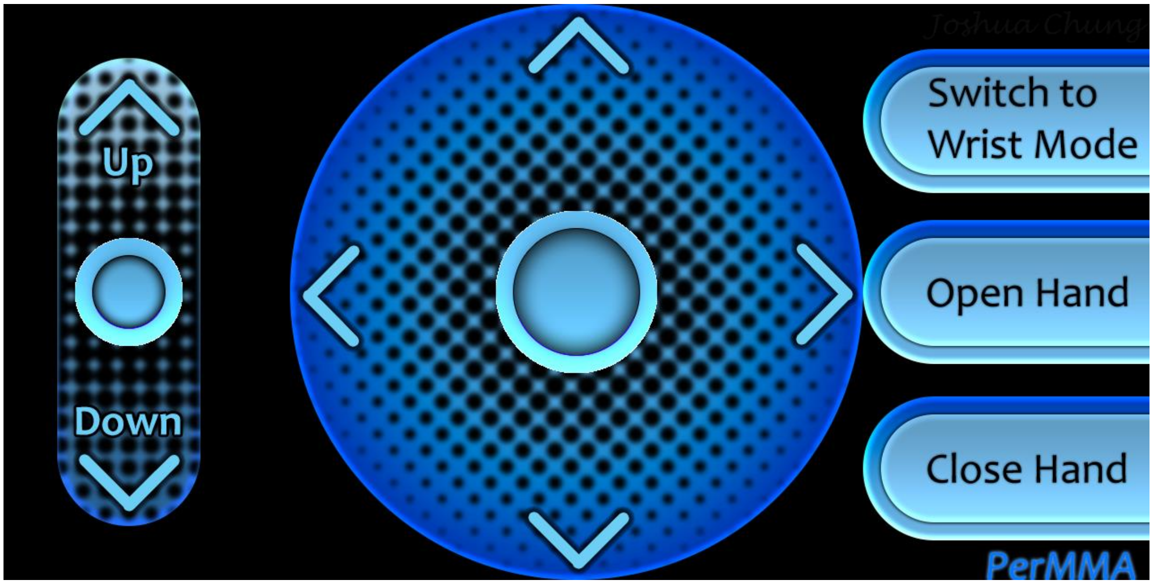

Figure 23. The PerMMA's touch-joystick GUI

Figure 23 shows a screenshot of the touch-joystick. The user can slide the smaller circle in the center of the controller in any direction within the larger circle, which has the same effect as moving the joystick in that direction. The small circle on the left side can be slid up or down to achieve the same result as twisting the joystick knob clockwise or counter-clockwise respectively. Holding down the “Open Hand” and “Close Hand” buttons on the right side of the controller open and close the ARM’s fingers, and the third button, which reads “Switch to Wrist Mode” in Figure 23, allows the user to toggle between translation and wrist modes of control.

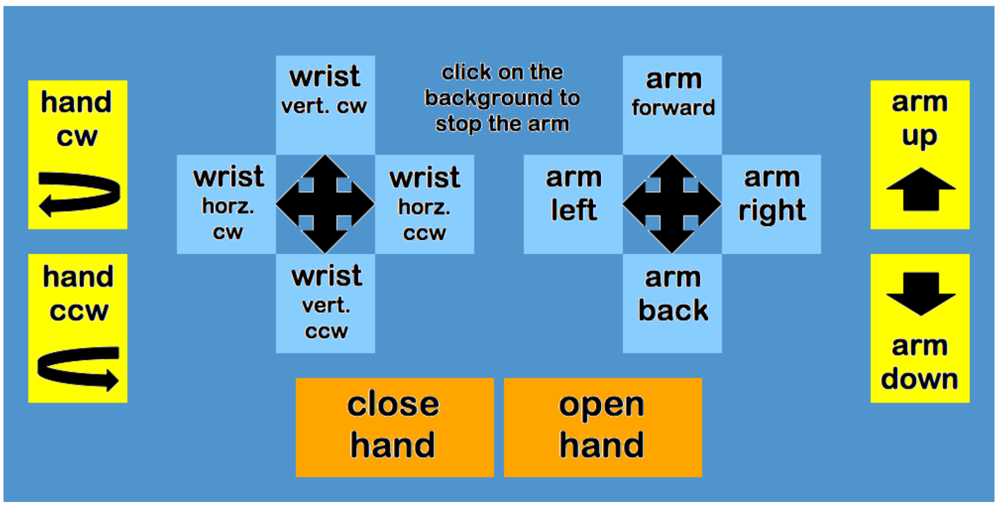

Figure 24. The PerMMA’s touch-keypad GUI

Touch-keypad (Figure 24) is another GUI developed that mimics the PerMMA keypad design [60], [61]. The touch-keypad uses buttons clustered according to the ARM motion, and pressing a button multiple times in a row causes the ARM to perform the motion faster and faster. The two exceptions to this are the “Close Hand” and “Open Hand” buttons, which must be held down and can only move the ARM at one speed. Clicking anywhere on the touch-keypad’s background causes the ARM to stop all motion.

The PerMMA touchscreen user interfaces were developed on two platforms for the local and remote users: Android and Ubuntu Linux. The Android phone or tablet provides the GUI, which is controlled with the smartphone's touchscreen, and sends the user's input to the computer through a Bluetooth connection. The computer then moves the ARM accordingly. The Ubuntu Linux user interface was controlled with events of the mouse click and drag and the button-click. In combination with a camera, a remote caregiver can access to the computer via a Wi-Fi connection from the remote operators' smartphone or tablet, controlling the ARM using a GUI, receive visual feedback from the cameras on the PerMMA. In this way, the remote operator can provide manipulation assistance using mobile devices and does not need to be sitting next to a computer.

Figure 25. The PerMMA touch-joystick App and the ADL task board

5.4.2.2 Performance Evaluation of Touchscreen User Interfaces

In order to verify the systematic viability in providing decent manipulation assistance with PerMMA, four manual interfaces were examined: the touch-joystick, touch-keypad, teleoperation-touch-joystick, and the original 3-axis joystick. The difference between the touch-joystick and teleoperation-touch-joystick is the connection and user's location. The touch-joystick connects to the PerMMA via Bluetooth when the user is sitting in the wheelchair; the teleoperation-touch-joystick connects via WiFi with visual feedback from the PerMMA camera. Performance of four user interfaces were evaluated with two tasks on the ADL task board [32]: Big Button and Elevator Button (Figure 25), which are two of the most sensitive Fitts' law based tasks (4.4.7). It consists of having subjects use an ARM to perform different tasks and recording the success rate and completion time. One of the developers performed each task twenty times using four controllers, and all completion times were recorded. The fifteen fastest completion times for each controller were used in our calculations.

5.4.2.3 Results and Discussion

A one-way repeated measures ANOVA was conducted to compare the effect of the touchscreen user interfaces on task completion time and ISO 9241-9 throughput from the fifteen trials using 3-axis joystick, touch-keypad, touch-joystick-teleoperation, and touch-joystick. There was a statistical difference found among the user interfaces (Table 17). Post hoc tests using Bonferroni correction revealed that completion times and throughputs were statistically different between each controller ($p < .001$ in all pairwise comparisons).

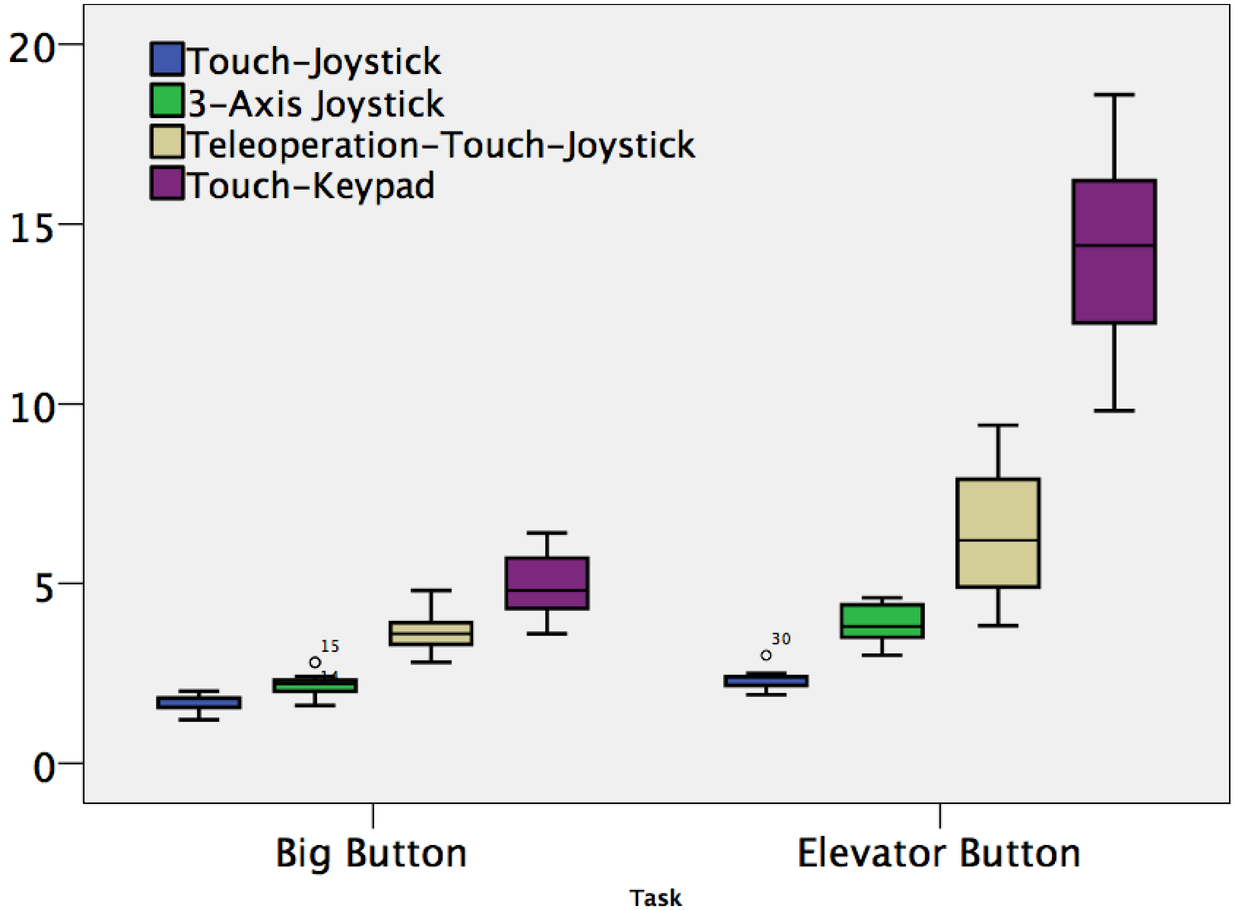

Figure 26. The boxplot of task completion times between the four controllers

Figure 26 shows the boxplot of the fifteen fastest completion times for each of the four user interfaces tested when the performing the big button and elevator button tasks. Also notable is the touch-keypad's slow performance on the elevator button task—its fastest time was more than a half second slower than the next slowest time on any of the other user interfaces. In Figure 27, the touch-joystick demonstrated statistically larger ISO9241-9 throughput than other controllers. This highest throughput suggested that the touch-joystick was the most efficient solution for the tester.

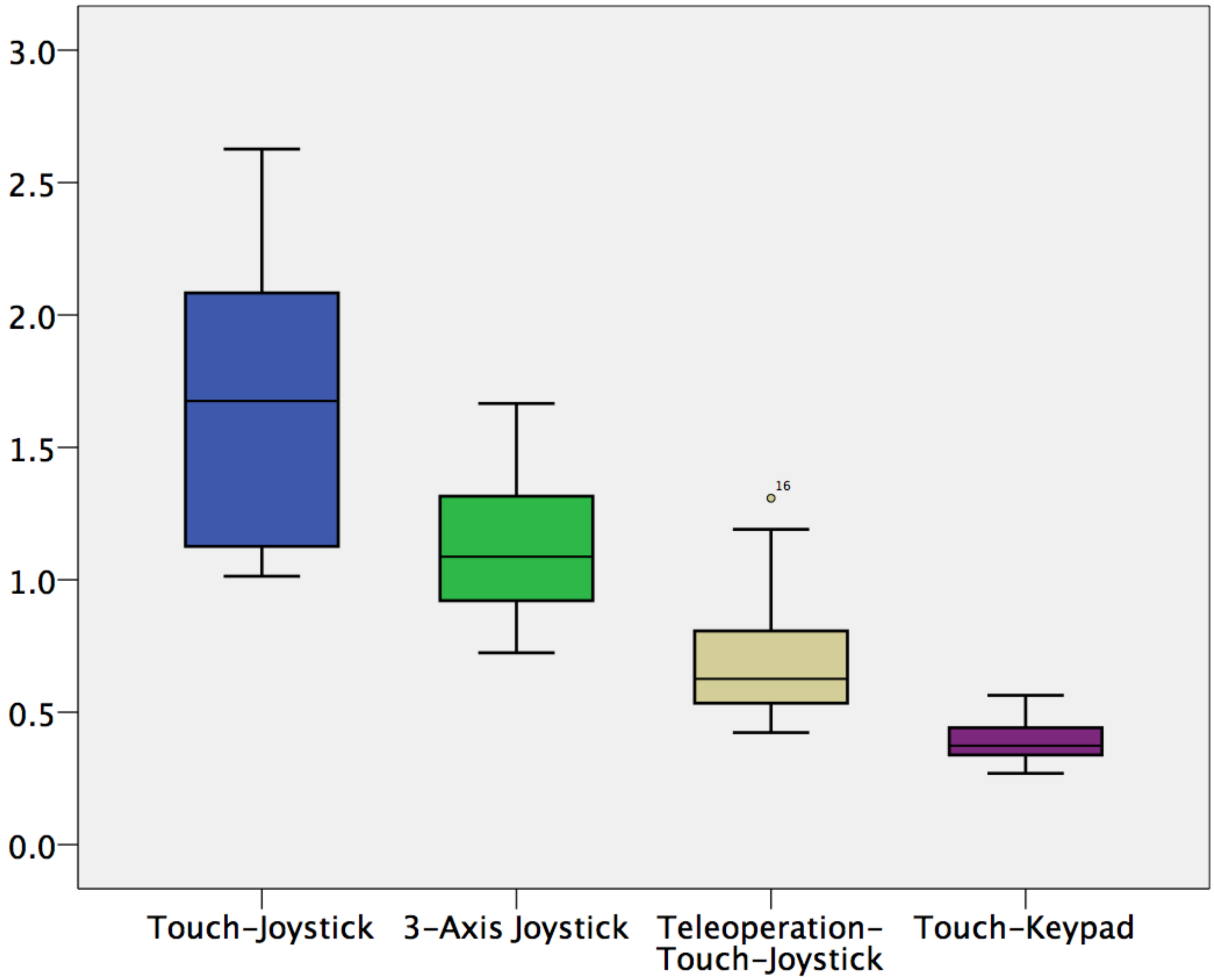

Figure 27. The comparison of ISO 9241-9 Throughput between each controller

Table 17. Task completion time of the manual user interfaces

user interface (n=15)	Touch-Joystick	Teleoperation-Touch-Joystick	Touch-Keypad	3-Axis Joystick	F(3,12)	p
Big Button (ID=2.034)	1.7±0.2	3.7±0.6	4.9±0.9	2.2±0.3	135.337	<.001*
Elevator Button (ID=5.006)	2.3±0.3	6.3±1.8	14.4±2.8	3.9±0.6	380.761	<.001*
ISO 9241-9 Throughput	1.69±0.54	0.71±0.23	0.39±0.83	1.13±0.25	375.650	<.001*

ID is the index of difficulty defined by the ISO 9241-9

The touch-joystick shows statistically highest throughput and lowest task completion time among all controllers. One potential reason for the touch-joystick outperforming the joystick is the slider design. This may suggest that a slider design with indication is a more intuitive or easier motion than twisting the joystick. During the testing, we observed less up-and-down directional errors using a touch-joystick. The multi-touch motions facilitated accelerating task performance by moving in three directions simultaneously. The touch-keypad's design makes it easy to accelerate the ARM, but more difficult to decelerate. However, this may be useful for people who cannot use other controllers.

5.5 AUTONOMOUS INTERFACE

5.5.1 Evaluation of Autonomous Interface

A study [37] monitored the ADLs of an able-bodied participant for five days and identified 3964 activities based on the International Classification of Functioning, Disability and Health (ICF). Among these activities, the most frequent task for self-care (d5 – ICF code) is drinking. The drinking task includes several of the most frequent mobility tasks for carrying, moving, and handling objects (d430 – d449) such as lifting (d4300), putting down objects (d4305), manipulating (d4402), and carrying in the hands (d4301). Therefore, we evaluated the autonomous interface using a drinking task, which is one of the most frequently used self-care daily tasks that requires multiple actions and complex manipulation skills.

5.5.1.1 Subtasks

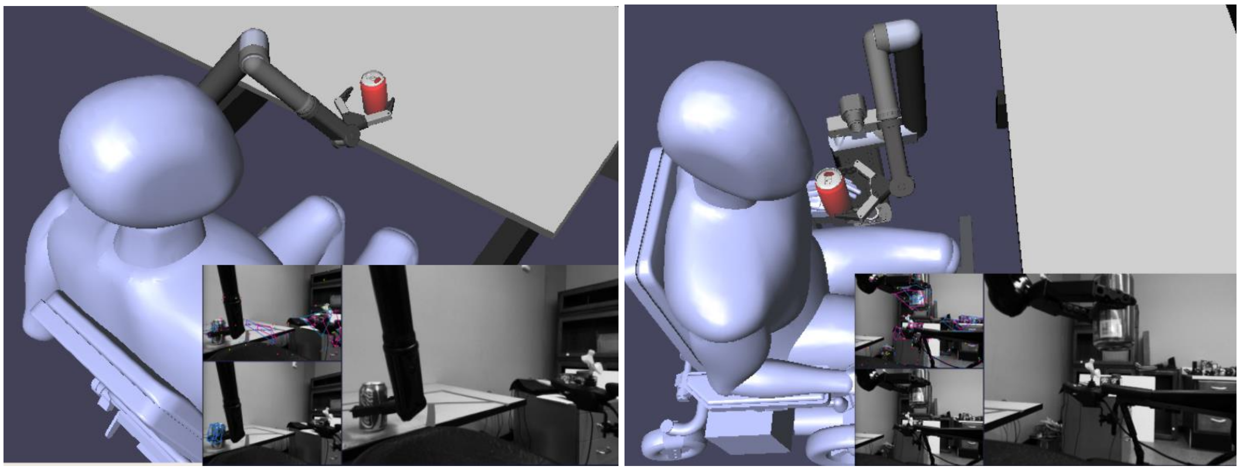

Figure 28. PerMMA autonomous interface

The drinking task was simplified into four subtasks: detection of the drink, planning and pickup of the drink on the table, bringing the drink to the proximity of the user, and placing it back onto the table. We used a soda can as the drink for this task since it is a common drink, but the algorithms also work for other kinds of drinks. Python scripts were developed to control the flow of states in the drinking task and manage error recovery strategies. The state flow is shown in Figure 28. Any failure during the movement subtasks was recorded and treated as a failed trial. In addition, for the safety of the occupant, a trial with any collision with the wheelchair user were rated as a failed trial.

Two starting locations as shown in Figure 29, easy and difficult, were used to evaluate the capability of the system in handling difficult tasks. The easy start location had the gripper above the table with no occlusion between the gripper and the soda can. In the difficult start location, the gripper started under the table. In the difficult configuration, the table was a long and large occlusion between the gripper and drink, and there was only a 3cm gap between the ARM's elbow joint and the table.

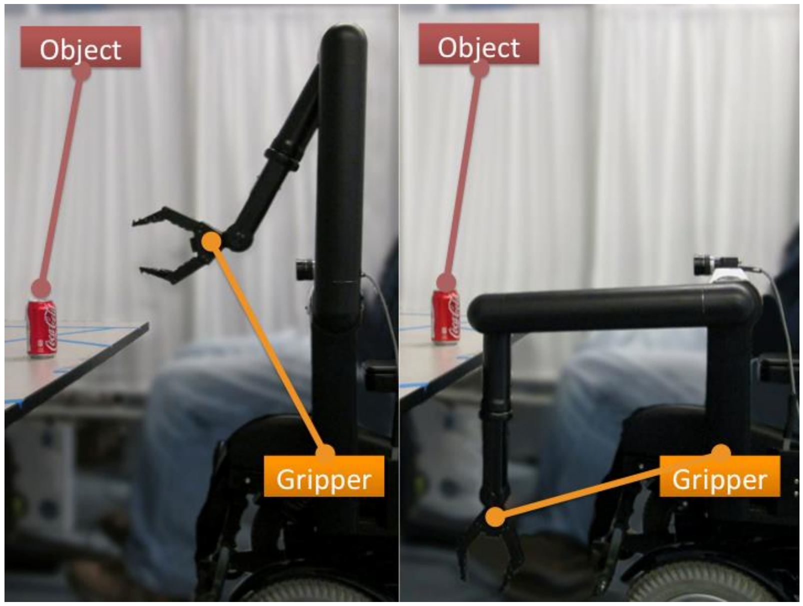

Figure 29. Testing start locations (left: easy; right: difficult)

5.5.1.2 TSR Parameters for CBiRRT

The TSR defines the constraints that limit the CBiRRT path planning from searching unwanted trajectories or unwanted end-effector poses. The Bound B^w in the TSR is defined as (1).

$$B^w = \begin{bmatrix} x_{min}, x_{max} & y_{min}, y_{max} & z_{min}, z_{max} \\ yaw_{min}, yaw_{max} & pitch_{min}, pitch_{max} & roll_{min}, roll_{max} \end{bmatrix} \quad (1)$$

The min and max indicate the lower and upper boundary of the constraint. For example, the B^w = [0,0; 0,0; 0,0; 0,0; 0,0; -π/2,π/2] indicates that there is no freedom in the xyz direction as well as the yaw and pitch angles but the roll angle allows rotation from -90 to 90 degrees.

Another example of B^w = [-100,100; -100,100; -100,100; 0,0; 0,0; -π,π] represents that the xyz directions and roll angle allow movement but not the yaw and pitch angle.

For the subtask of picking up the soda can, we only constrained the end-effector. However, for the other subtasks of conveying the drink, there was one more constraint applied for preventing the drink from spilling. The parameters applied are listed in Table 18. We set the time limit for searching end-effector solutions to 5 seconds and the time for searching the entire trajectories to 30 seconds for each subtask. The iterations number for smoothing trajectory was 150.

Table 18. TSR parameters of the subtasks

Subtask	Bw	Bw Type
Pickup the drink	[0,0;0,0;0,0;0,0;0,0; -π/2,π/2] if the drink is at the left hand side of the ARM gripper	Goal pose
	[0,0;0,0;0,0;0,0;0,0; π/2,3π/2] if the drink is at the right hand side of the ARM gripper	Goal pose
Bring the drink to the user	[-0.35, -0.4, 1.05]	User's mouth
	[0,0;0,0;0,0;0,0;0,0; -π/2,π/6]	Goal pose
	[-100,100;-100,100;-100,100; 0,0;0,0; -π ,π]	Constrain
Place the drink on the table	[0,0;0,0;0,0.1;0,0;0,0;-π/2,π/2]	Goal pose
	[-100,100;-100,100;-100,100; 0,0;0,0; -π ,π]	Constrain

The goal poses are the limitation assigned to the end of the trajectory. For pickup and place-down, the goal poses were limited to pointing forward or sideward to increase reachable range. For bringing the drink to the user, the goal pose was assigned to facing backward so that the user could access to. Constrains are the additional limitation or boundaries other than the physical objects set to the moving space. There is no boundary limitation for moving to the drink. In this phase, the ARM might move freely to the drink. While holding the drink in the hand, constrains with limitations on the rotation in X and Y axes was regulated to prevent spilling so that the ARM could only move with the drink straight. The user's mouth is a pre-defined location that may be different between individuals.

5.5.1.3 Outcome Measures

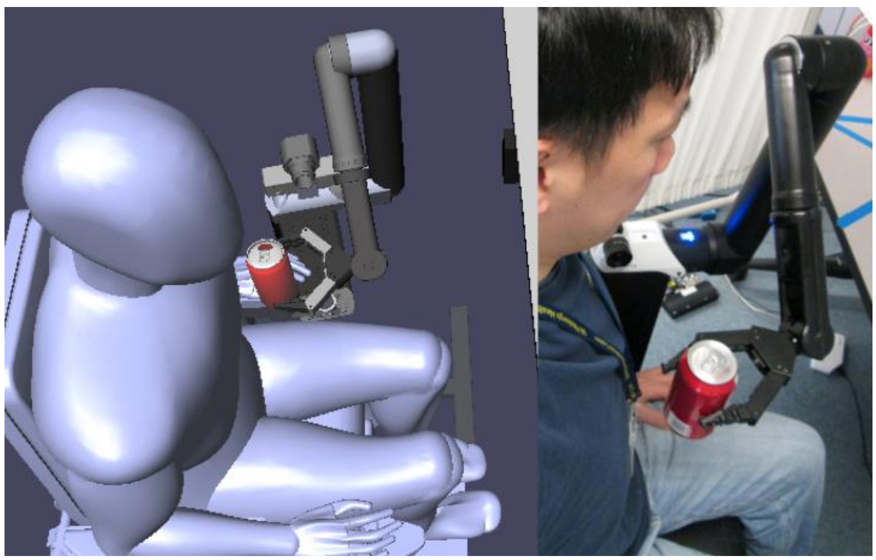

Figure 30. The planning level (right) and system level (left)

The system was tested on three levels: the detection level, the planning level, and the whole system level. The detection level only evaluates the MOPED in detecting different orientations of the soda can. The soda can faces the camera with different rotation angles and distances. The planning level (Figure 30) evaluates the ability and success rate of the CBiRRT with OpenRAVE simulation in searching trajectories for each subtask. In this test, the soda can was randomly placed in front of the ARM either inside or outside its working space. The whole system level test evaluates the system, including moving the ARM to physically picking up the drink and bringing it to the user, to see how the planning strategies work in the real world. The soda can was randomly put on the table inside the working space and recognition area (inside the blue tape).

The success rate and completion time are the major outcome measures for each subtask. The time of detection was determined by the start of the detection state to successfully finding the drink. For the path planning level, the success rate of planning algorithms and the time needed for planning is reported, including the robot simulation. However, we added one more condition that if the time of planning and robot simulation exceeds 60 seconds, i.e. slower than human performance [60], we rated this trajectory as failed. The location failures to find trajectories were also recorded. The average speed was defined by equation (2).

$$Speed = \frac{\sqrt{(x_T - x_0)^2 + (y_T - y_0)^2 + (z_T - z_0)^2}}{T} \quad (2)$$

where T is the time from the start of path planning to the end of robot movement. x_T, y_T, z_T are the position at the end of the trajectory and x_0, y_0, z_0 are the start position. Table 19 shows the outcome measures for each subtask.

The speed in the planning level was computed by the simulated ARM, which was faster than the real ARM. In this way, the researcher could quickly verify the ARM motion and make decision on fail or success. The trajectory with slower speed indicated that there are eccessive movement in it, which may be continuous wrist rotation or waving ARM in an opened space. The trajectory with higher speed implied that this might be an optimal trajectory. Therefore, higher average speed implied that it is easier to find an optimal trajectory.

Table 19. Measurement of Subtasks

Subtask	Measurements
Detection	Successful rate Time completion
Pickup the drink	Successful rate Time completion/Speed Fail reasons
Bring the drink to the user	Successful rate Time completion/Speed Fail reasons
Place the drink on the table	Successful rate Time completion/Speed Fail reasons

5.5.2 Results

The results of completion time, moving speed, and the success rate are shown in Table 20.

Table 20. Test Results of the autonomous functions

Subtask		**Outcome measure**		
		Complete. time (second)	**Speed (mm/s)**	**#Fail/#Total Success Rate**
Planning level (start above the table)	**Pickup**	3.62±0.80 (1.32~7.70)	134.6±41.4 (55.4~358.0)	5/1365 99.6%
	Drink	2.51±0.99 (0.86~5.95)	339.2±121.9 (141.1~777.8)	47/1127 96.17%
	Place	1.83±0.47 (0.80~4.67)	436.3±95.2 (168.5~847.4)	0/1170 100%
Planning level (start under the table)	**Pickup**	9.50±9.74 (1.93~58.53)	79.3±39.1 (6.4~210.4)	18/558 96.8%
	Drink	2.6±0.9 (1.0~5.4)	322.6±115.0 (139.7~730.6)	37/472 92.2%
	Place	1.9±0.5 (0.9~4.6)	425.9±94.0 (158.1~782.1)	0/505 100%
System level	**Detect**	0.45±0.12 (0.20~0.68)	N/A	100% (0°) 92% (45°)
	Pickup	12.1±2.6 (7.6~18.0)	47.5±5.8 (26.8~50.7)	18/62 70.1%
	Drink	9.58±1.85 (6.6~15.4)	74.6±12.3 (50.3~99.3)	7/38 81.6%
	Place	10.6±2.7 (5.4~17.0)	75.8±17.4 (48.1~125.8)	0/30 100%

[a.] Completion time is presented as average ± standard deviation (minimum ~ maximum)

5.5.2.1 Sensing Performance

The average time for MOPED detection was 0.45 second for a single soda can and 1.75 seconds for multiple objects shown in Figure 31. However, the faces with less SIFT features were harder to recognize (Shown in Figure 6). Detection success rates were 100% at 0 degrees, 92% at 45 degrees, and unable to identify at 90 degrees. Moreover, the MOPED distance estimation was 1 inch shorter when the soda can was more than 28 inches away.

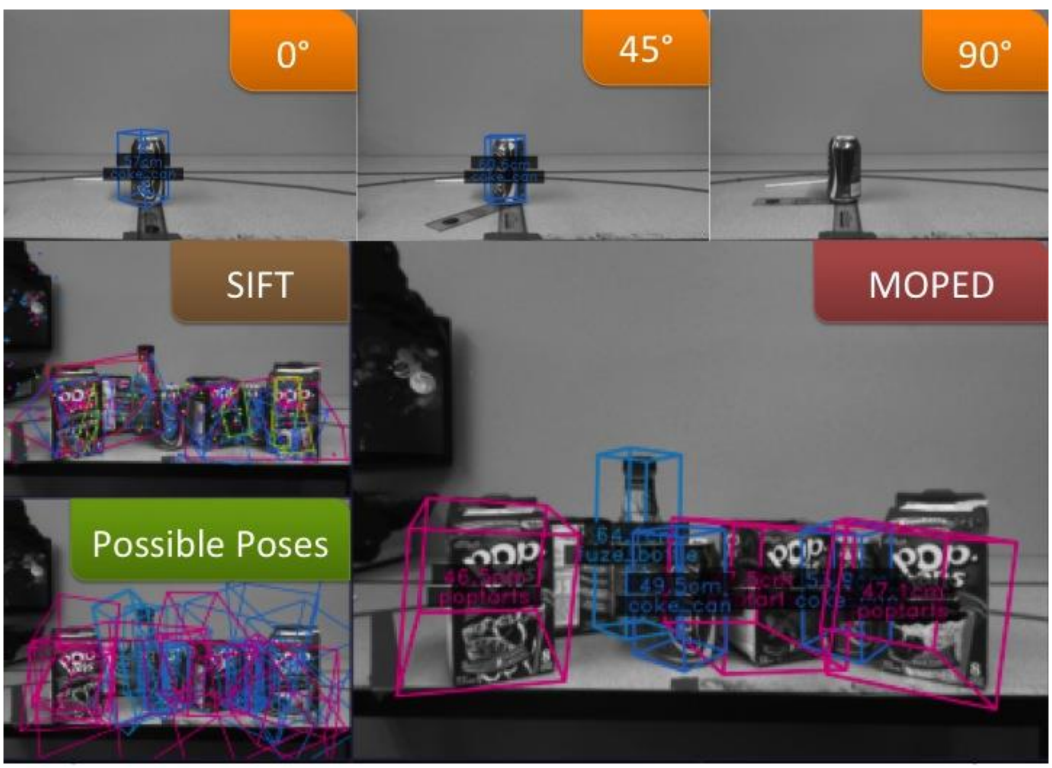

Figure 31. Different faces and poses of soda recognized by MOPED

5.5.2.2 Planning and Performing Performance

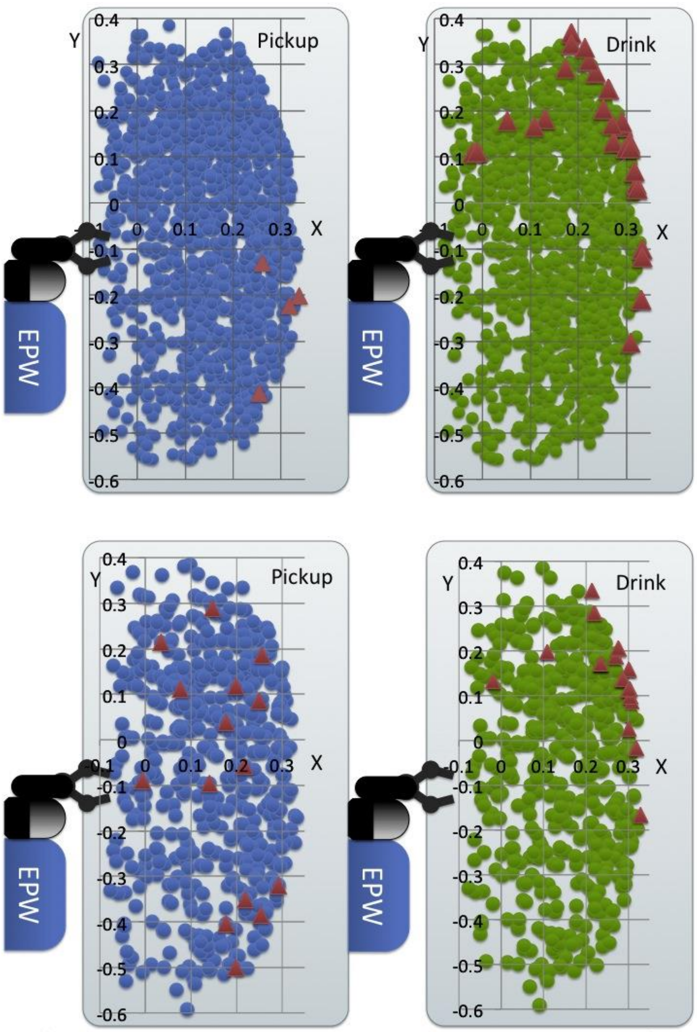

Figure 32. Success and fail location on the table (upper left: Pickup subtask from higher start location, upper right: Drinking subtask from higher start location, lower left: Pickup subtask from lower start location, lower right: Drinking subtask from lower start location)

Overall, the path planning simulations show a very high success rate (> 92%). The pickup subtask was slower than the drink and place subtasks. Planning from the easy location was faster than from the difficult position. Figure 32 plots the locations on the table that have been tested for pick-up and drinking subtasks. The red triangles indicate the location from which the ARM was unable to complete the subtask. The ARM and electrical power wheelchair (EPW) was drawn on the side of the table. The pick-up subtask, starting from under the table showed more random failures than starts from above the table. More failures were located on the left side of the ARM. The failures on the right side of the ARM were close to the limit of the workspace. In the drinking subtask, most of the failures were found at the edge of the ARM workspace. There were no failures found on the right side of the ARM.

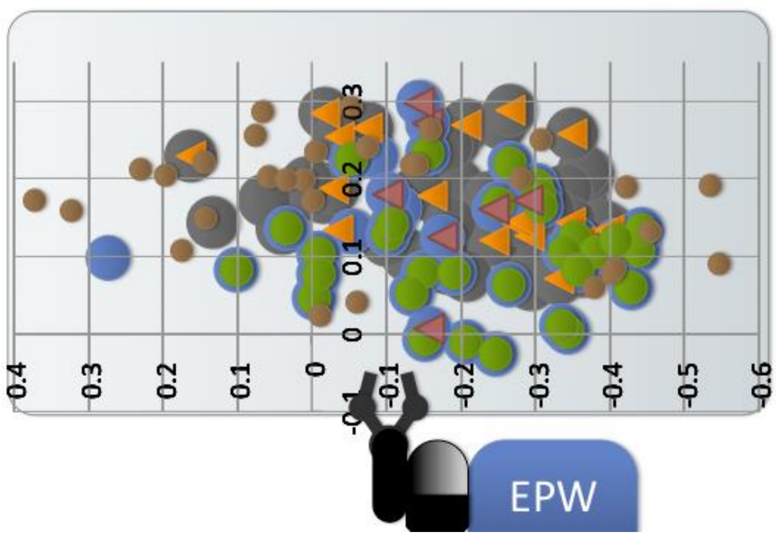

Figure 33. The successful and failed locations on the table of four subtasks in the system level test. Gray: success detection; Blue: successful pickup; Orange: failed pickup; Green: successful drink; Red: failed drink; Brown: place locations

In the system test, the overall success rate was 70.1% for the pick-up subtask and 81.6% for the drinking subtask. The speed of the pick-up subtask was slower than the simulation. The completion time of the ARM in the subtasks was longer than the simulation (Table 21). The entire drinking task was completed within 40 seconds. The successful and failed locations on the table of four subtasks are plotted in Figure 33.

Table 21. Comparison between autonomous interface and manual user interface in the task of bringing the drink to the user's mouth

user interface	**Completion Time (second) Mean±SD (range)**	**#Fail / #Total Successful Rate**
Autonomous Interface	9.58±1.85 (6.6~15.4)	7/38 81.6%
3-Axis Joystick (n=10)	31.53±19.22 (8.00~59.41)	0/10 100%
Keypad (n=10)	88.68±61.00 (15.65~222.84)	0/10 100%

In comparison with WMFT-ARM, the item 4 – lift can to mouth was to simulate drinking which is a similar action to the drinking task with autonomous interface in [57]. The results show that, on average, the autonomous interface was three times faster than the 3-axis joystick and nine times faster than the keypad. However, it was noted that there were seven out of 38 trials when the autonomous interface failed with unsecured grasp all occurred on the subtask of bringing the drink to the mouth. In the contrast, although the manual user interface was slower, the successful rate was ensured with each participant.

5.5.3 Discussion

5.5.3.1 Sensing

The MOPED relies on the SIFT features for establishing object pose hypotheses. The object with fewer SIFT features has less chance of being recognized. The other limitation was the calibration of the camera. Although the camera was calibrated before tests to eliminate distortion and skew factors form the lens, the error in the camera internal parameters may be amplified if the object was away from the camera. Therefore, at the edge of the workspace, the estimated distance error was about 1 inch.

5.5.3.2 Planning and Performing

The planning simulations demonstrated a very high success rate at the easy and difficult start locations. Most of the planning failures occurred at the edge of the workspace. This was probably because of the singularity point in the kinematic model when the robot is fully extended. For the subtask of picking up and bringing the drink to the user from the difficult location, the robot failed more often on its left hand side (0.2m away from robot base). This is similar to a human's arm, in that it is harder for a human to bring an object far away from the body. The robot had no problems in picking up and bringing to the user when the soda can was in front of the wheelchair and about 0.3m from the edge of the table.

During the system level test, the major cause that the pick-up failed was when the MOPED positioning error was located at the far end away from the camera. The failures were likely caused by the aggressive trajectories. These kinds of trajectories include some motions with either 0.5” tolerance to the objects or arm extended more necessary. The drinking subtasks usually failed with unsafe grasping that dropped the object during motion. These failed moves can be improved with better trajectory strategies. Although the speed was slower than the simulation, it can be increased by re-sampling the trajectory to fewer waypoints so that the ARM has fewer stops during the movement.

5.5.4 Conclusion

The PerMMA system with autonomous functions was developed and evaluated with a drinking task with multiple actions that included carrying and handling the drink. The drinking task was divided into four subtasks: detection, picking up the drink, bringing the drink to the user, and placing the drink on the table. Success rates and the average task completion time for each subtask were computed. The entire drinking task was completed within 40 seconds.

5.6 ASSISTIVE SLIDING-AUTONOMY INTERFACE

5.6.1 Development of Assistive Sliding-Autonomy Interface

The assistive sliding-autonomy user interface was developed as the framework to incorporate wheelchair users and autonomous manipulation. This assistive sliding-autonomy interface provides various levels of assistance to meet ADL manipulation needs and manual user interfaces. For example, the moving dimensionalities can be reduced when conveying liquid to prevent spilling. One DOF control allows the user to control the speed of the ARM moving through the pre-planned trajectory from the autonomous interface. Two level of assistance was developed (Figure 34): reduced DOF cooperation, and 1DOF control. In the reduced DOF cooperation, the ARM moves along the trajectory from the CBiRRT and the user can still make linear or angular adjustment with reduced DOF. The 1DOF control is to approach the speed along the planned trajectory going forward, stop, or backward.

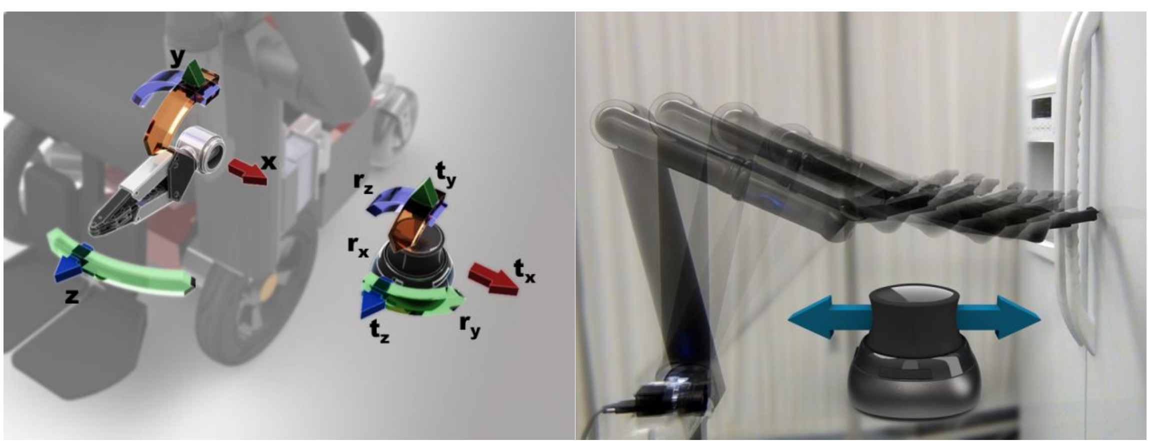

Figure 34. The assistive interface with six DOF (left) and one DOF (right) control

For users with pathological hand tremor, this assistive sliding-autonomy interface can apply filters to smooth the additive noise. This interface can also add gains to amplify the movement if the user has weak strength or limited range of motion in certain directions. There are three variations of assistive modes: fully autonomous or manual control, transitional assistance, and 1DOF control.

Input from the 6DOF human interface is represented as $\boldsymbol{X}$. The general form of $\boldsymbol{X}$ is

$$\boldsymbol{X} = [t_x \quad t_y \quad t_z \quad r_x \quad r_y \quad r_z]', -1.0 \leq t_x, t_y, t_z, r_x, r_y, r_z \leq 1.0 \tag{1}$$

The components in $\boldsymbol{X}$ are the translational and rotational readings from the Spacenavigator input device. The range is between -1.0 and 1.0. These components can be used for speed or positioning control. In order to smooth uncontrolled tremor, the readings are filtered using a moving average.

The optimized trajectory found from path planning algorithms is T. This trajectory T is a set of waypoints. Each waypoint contains end effector positions and end effector velocities. It can be described as

$$\boldsymbol{T} = \{\boldsymbol{W}_i\}, i = 0, 1, \dots n \tag{2}$$

$$\mathbf{W}_i = [\boldsymbol{P_i} \quad \dot{\boldsymbol{P}}_{\boldsymbol{i}}]' \tag{3}$$

In (3), $\boldsymbol{P_i}$and $\dot{\boldsymbol{P}}_{\boldsymbol{i}}$ are the waypoint position and velocities.

$$\boldsymbol{P_i} = [x_i \quad y_i \quad z_i \quad \theta_{xi} \quad \theta_{yi} \quad \theta_{zi}]' \tag{4}$$

The generic discrete form of assistive interface can be described as the sum of the next planed robot position or velocity and a function of the current user input. The $\boldsymbol{F}(\boldsymbol{X_i})$ and $\boldsymbol{G}(\boldsymbol{X_i})$ are arbitrary functions of the current user input x_i to make either positioning or speed adjustments. The coefficient α determines the amount of the effect by the planned positions and velocities.

$$\begin{cases} \boldsymbol{P}^*_{\boldsymbol{i+1}} = \alpha \boldsymbol{P}_{\boldsymbol{i+1}} + \boldsymbol{F}(\boldsymbol{X}_{\boldsymbol{i}}) \\ \dot{\boldsymbol{P}}^*_{\boldsymbol{i+1}} = \alpha \dot{\boldsymbol{P}}_{\boldsymbol{i+1}} + \boldsymbol{G}(\boldsymbol{X}_{\boldsymbol{i}}) \end{cases} \tag{5}$$

The first mode is fully manual or fully autonomous. In fully autonomous motion, we can set the $\boldsymbol{F}(\boldsymbol{X_i})$ and $\boldsymbol{G}(\boldsymbol{X_i})$to zero and α to one. The ARM is totally in manual control when α is set to zero. When simply applying (5) as a fully 6DOF manual velocity control (Fig. 6), (5) can be revised as

$$\dot{\boldsymbol{P}}^*_{\boldsymbol{i+1}} = \boldsymbol{G}(\boldsymbol{X}_{\boldsymbol{i}}) = \boldsymbol{A}\boldsymbol{X}_{\boldsymbol{i}}, where\ \boldsymbol{A} = \begin{bmatrix} \begin{matrix} a_1 & 0 & 0 \\ 0 & a_1 & 0 \\ 0 & 0 & a_1 \end{matrix} & \boldsymbol{0} \\ \boldsymbol{0} & \begin{matrix} a_2 & 0 & 0 \\ 0 & a_2 & 0 \\ 0 & 0 & a_2 \end{matrix} \end{bmatrix} \tag{6}$$

The $\boldsymbol{A}$ is a 6x6 matrix constructed by two scalars – $a_1$and a_2. These scalars are the gains to amplify the translational and rotational motion from user input $x_i$to robotic position and orientation change.

The second mode is translational assistance. While conveying food or drink, this mode allows the ARM moving autonomously with limited manual adjustment e.g. the user may need to adjust the drink pose without spilling if a straw in a closed cup is not accessible. These limitations keep the orientation of the grasped object by eliminating the rotational components in $\boldsymbol{A}$.

$$\dot{\boldsymbol{P}}^*_{\boldsymbol{i+1}} = \dot{\boldsymbol{P}}_{\boldsymbol{i+1}} + \boldsymbol{A}\boldsymbol{X}_{\boldsymbol{i}}, where\ \boldsymbol{A} = \begin{bmatrix} \begin{matrix} a_1 & 0 & 0 \\ 0 & a_1 & 0 \\ 0 & 0 & a_1 \end{matrix} & \boldsymbol{0} \\ \boldsymbol{0} & \begin{matrix} 0 & 0 & 0 \\ 0 & a_2 & 0 \\ 0 & 0 & 0 \end{matrix} \end{bmatrix} \tag{7}$$

In (7), the rotation along the y-axis is kept so that the user can still orient the food or drink to find the proper pose for eating or drinking.

The other example of translational assistance mode is to open a refrigerator door. In this task, the ARM only moves and rotates in the XZ plane. This setting allows the user to adjust gripper position in case the refrigerator model or hinge position for path planning is not accurate. Therefore, (5) can be expressed as

$$\dot{\boldsymbol{P}}^{*}_{\boldsymbol{i+1}} = \dot{\boldsymbol{P}}_{\boldsymbol{i+1}} + \boldsymbol{A}\boldsymbol{X}_{\boldsymbol{i}}, where\ \boldsymbol{A} = \begin{bmatrix} \begin{matrix} a_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_1 \end{matrix} & \boldsymbol{0} \\ \boldsymbol{0} & \begin{matrix} 0 & 0 & 0 \\ 0 & a_2 & 0 \\ 0 & 0 & 0 \end{matrix} \end{bmatrix} \quad (8)$$

In the above two modes, the ARM can still move autonomously when there is no user input. However, the user may like to control the speed while approaching some objects in some situations. The ARM moves along the planned trajectories, but the user can control it to go faster or slower or make it stop, e.g. while moving in an open environment, ARM can be accelerated to save time; but while moving in a complex environment with other objects around, it would be safer to slow down so that the user could make adjustments promptly if there is perceptual or robotic positioning error. Here we introduce some of the ways to achieve the 1DOF control mode.

$$\boldsymbol{P}^{*}_{\boldsymbol{i+1}} = \boldsymbol{P}_{\boldsymbol{i+ax_i}} \quad (9)$$

While accelerating the ARM motion in the opened space with no obstacle near, we can speed up the robot by skipping some waypoints. This saves time by moving through all the waypoints.

On the other hand, when decelerating, the speed can be reduced by

$$\dot{\boldsymbol{P}}^{*}_{\boldsymbol{i+1}} = ax_i\dot{\boldsymbol{P}}_{\boldsymbol{i+1}} \quad (10)$$

Another way is to determine the next position using trajectory segmentation and line extraction [68] based on the distance to current position. This distance is determined by the user input.

5.6.2 Evaluation of Assistive Sliding-Autonomy Interface

As mentioned in Chapter 2, a sequential task is difficult to be evaluated with Fitts' parameters because of large variance in sub task sequence and task completion. The assistive sliding-autonomy interface was examined with a complicated sequential task, retrieving a drink from a refrigerator that requires successful completion of each subtask. Figure 35 shows the states and level of assistance in completing the task. During approaching the door handle and soda can, the user can accelerate the robot to the door handle or soda can and slow down while moving into grasping pose with 1DOF control. While opening door, the assistive interface is changed to reduced DOF cooperation (3DOF). The ARM opens the door autonomously but the user may correct simultaneously. It works in the same way while bringing the soda can to the user. If any of these subtasks failed, the user can press a key to stop the ARM and correct it manually. The switching between the states is determined by the pose of the ARM and detection of soda can. For example, if the assistive interface detected a soda can and the ARM was at the soda can, the state would switch to the bring drink to mouth. Another example is that if there was no soda can detected and the ARM was at the resting position, the next state would be moving to the door handle.

The PerMMA was able to complete entire task successfully with the autonomous interface. However, in order to examine the usefulness of the assistive sliding-autonomy interface when the PerMMA was performing incorrectly, random errors were deliberately added into each state to evaluate the capability of the assistive sliding-autonomy interface in overcoming fail situations. Otherwise, with the autonomous interface working flawlessly every time, there was no need for a user to intervene. The failure situations in this retrieving and drinking task were door handle positioning errors, door hinge modeling errors, drink pose estimation error, and gripper drop due to overloading. The door handle's location was offset by a random number to simulate detection error. While opening the door, we added random hinge position errors so that the ARM trajectory was not centered with the actual physical refrigerator door hinge. After opening the door and identifying the soda can with MOPED, random translational errors were added to the drink position. While bringing the soda can to the user, extra downward positioning errors were applied to simulate the drop from moving a heavy object.

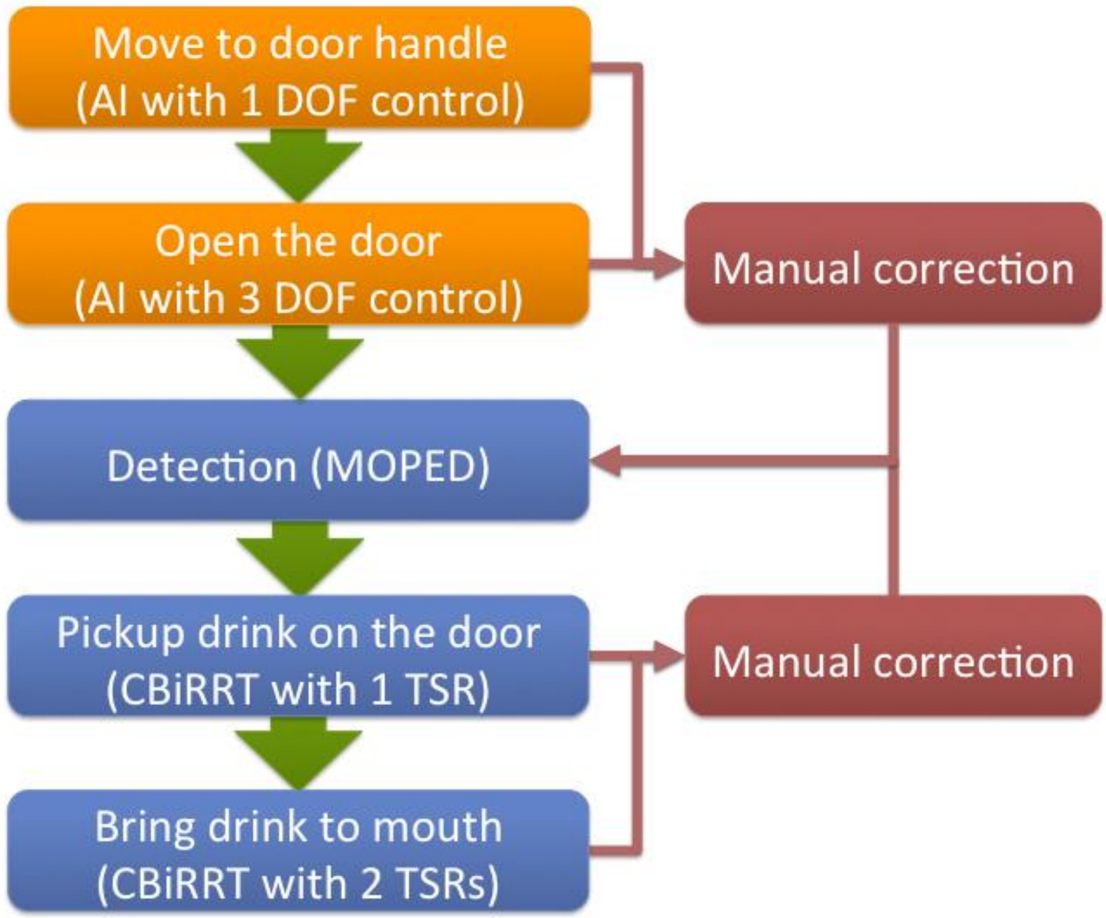

Figure 35. States and subtasks of the testing procedure for the assistive sliding-autonomy interface

5.6.3 Results

The performance of an assistive sliding-autonomy interface was evaluated with 30 trials, while placing the soda can in a random location inside the refrigerator door. The entire task takes about 2.5 minutes on average to complete including the computation time for object detection and path planning. Because the testing was to examine the sequential task as a whole and individual random errors between trials, we only report the average time and success rate. It may be longer if the random error in subtask is large and the ARM needs to manually recover. However, in comparison with 18 minutes performed in a study [69] with keypad manual interface, the assistive sliding-autonomy interface shows dramatic improvement in completing sequential tasks.

Figure 36. The demonstration of the assistive sliding-autonomy interface. It is also available on the YouTube (http://www.youtube.com/watch?v=Vy21KBhPChc)

When resolving with door handle positioning error, the 1DOF trajectory control helps to go backward to a more appropriate grasping pose. While opening the door with hinge modeling error, the error can be dynamically corrected without stopping or slowing down the robot motion or recalculating the trajectory. When an error occurred, it may noticeably observed that the ARM is moving to a wrong direction in the opening subtask. By simultaneously adjusting through the ARM, the ARM can immediately resume the opening action and smoothly finish the rest of the trajectory. After the door was opened and 1DOF trajectory control was applied to quickly approach to the soda can, the gripper position can be modified with the manual user interface to a more robust grasp pose. In the state of bringing soda can to the user with sudden drops, the user can still keep the drink straight and correct the pose errors with 4DOF translational control. Overall, all the trials were successfully completed with the assistive sliding-autonomy interface.

5.6.4 Discussion

For single action task such as pushing buttons, the autonomous interface may not show significant differences. But for the task required finer alignment or adjustment in the drinking task, it becomes a trade-off problem with the autonomous interface. The autonomous user interface shows increased performance with significantly reduced task completion time in the task of bringing a drink to the user. It also increased the chance of unsuccessful task completion. This reduced success rate would be more harmful when completing a sequential task that requires successful task completion in each subtask.

However, by incorporating with a sliding-autonomy interface, the success rate for sequential task was improved. As the errors from perception and ARM manipulation cannot be easily avoided, it is important to incorporate the user to supervise the autonomous manipulation with an interface that can simultaneously make adjustment while completing the task. As the result, to efficiently correct the fail or on the point of failing tasks, the framework of the assistive sliding-autonomy interface allows the user to seamlessly and dynamically correct and ensure the task completion without re-calculating trajectories or reset the ARM position. More importantly, the results showed that this assistive sliding-autonomy interface could be useful with pre-stored trajectories. In the subtask of the opening refrigerator door, the pre-stored trajectory is an arc centered at the hinge position with the gripper oriented toward the door handle. With dynamically adjusting the gripper position, the task was completed each time without accurate hinge position and re-planning the trajectory.

5.6.5 Conclusion

This chapter introduces PerMMA manual, autonomous, and assistive sliding-autonomy user interfaces that offer ARM users an intuitive way to efficiently complete ADLs in different level of complexity. With testing from single action task to complicated sequential task, we have demonstrated improved performance and success rate for ARM user interfaces. The improved PerMMA system was also introduced to better incorporate with different brand of ARMs and the mobile devices. The touchscreen user interfaces were introduced and evaluated with a common single action ADL, pushing different sized buttons. The results suggest the touch-joystick is a viable user interface and possibly even easier to use. The PerMMA framework of assistive sliding-autonomy interface was also developed and evaluated with the task of retrieving a drink in the refrigerator. Two types of incorporation between manual user interface and autonomous interface were developed. Both types of incorporation seamlessly combined manual input and path planners to complete complicated tasks with reduced human input commands and computational loading for re-planning. In addition, it also ensured the task completion in each subtask. It also shows the capability of reusing pre-stored trajectories such as opening doors.

5.6.6 Study Limitation

More testing with wheelchair users and people with difficulty using the joystick is needed before the PerMMA user interface can be proven useful. However, our results suggest that the PerMMA user interfaces could be an easier to use manually and autonomously both for users with impaired hand and arm function and those without. Detection for the refrigerator door and handle is not addressed in this research work due to the limitations of current object detection algorithms in processing the reflection or single colored objects. Implementing depth data from RGBD cameras may help with identifying the door and handle location. In addition, retrieving a drink from the refrigerator is only an initial step. There are various daily activities that we need to work on.

6.0 CONCLUSION AND FUTURE WORK

6.1 CONCLUSION

The ARM has shown the improvement in self-care and increased independence among people with severe upper extremity disabilities. With an ARM mounted on the side of an electric powered wheelchair, the ARM provides manipulation assistance in ADLs, such as picking up object, eating, drinking, dressing, reaching out, or opening doors. However, existing assessment tools are inconsistent between studies, time consuming, and unclear in clinical effectiveness. The inconsistency between studies makes it hard to conclude systematic clinical effectiveness of ARM usage. These inconsistent assessment tools also make it confusing when identify appropriate user interfaces for ARM users. Moreover, no normative data were published with these assessment tools. The lack of normative data and standard assessment tools would make clinicians hard to justify their intervention for ARM training, user interfaces, and AT prescription. Therefore, the goal of this research is to answer the two of the most important questions about ARM user interfaces: how well the current user interfaces perform and how we can make them better.

To answer the first question, we reviewed the existing studies that involved wheelchair users to identify the challenges of ARM performance and assessment in ADL tasks in Chapter 2. This review shows that 1) a standard performance evaluation tool is essential for assessing and comparing ARM user interfaces; 2) clinical acceptance and ADL relevance facilitate establishing clinical effectiveness and motivate users; 3) Fitts' parameters and trajectory analysis improve the generality with eliminating variance between task and environment; 4) The end users should include caregivers and family members who may also provide assistance using ARM.

In order to better assess performance between ARM user interfaces, we introduced an ADL task board evaluation tool in Chapter 3 that provides standardized, efficient, and reliable assessment of ARM performance. The study tested with power wheelchair users and able-bodied controls by comparing two commercial ARM user interfaces, joystick and keypad, reveals that there were statistical differences between these two user interfaces, but no statistical difference was found in the cognitive loading. The ADL task board demonstrated a correlated performance with an existing functional assessment tool, Wolf Motor Function Test. Through the study, we have also identified barriers and limits in current commercial user interfaces. The study results demonstrated moderate to high correlation to WMFT-ARM and higher sensitivity / responsiveness to change to the two commercial user interfaces, which suggests that the ADL task board is valid and sensitive to clinical intervention changes. These results are also a useful normative data of first time users, which can be used for clinicians and ARM suppliers developing training programs and for other ARM developers to develop better user interfaces.

To improve the ARM user interfaces, we introduced the developed PerMMA interfaces in Chapter 4, including manual physical and touchscreen user interfaces, autonomous interface, and assistive sliding-autonomy interface. The touchscreen user interface with touch-joystick GUI demonstrated improved task performance and higher ISO 9241-9 throughput on the standardized ADL task board. The performance is improved due to reduced error, better indication, and less mode changes. The PerMMA autonomous interface was introduced and evaluated with a multiple-action task, retrieving a drink and returning it. The PerMMA autonomous interface shows improved performance in comparison with the drinking subtest in the Adapted Wolf Motor Function Test using manual user interfaces. This finding reveals that the autonomous interface may perform faster than the manual user interface. However, the testing also reveals that the success rate would decrease due to error in sensing and performing. This finding suggests that the assistive sliding-autonomy interface is essential when resolving errors in the autonomous interface. The assistive sliding-autonomy interface also yields improved success rate in the complicated sequential task, retrieving a drink from a refrigerator. Instead of resetting ARM and re-planning and performing, the assistive sliding autonomy interface allows users to interact with the ARM with various DOF. The testing with deliberately additional positioning errors demonstrates that the assistive sliding-autonomy interface has the capability to ensure the task success without compromising the task completion time. The assistive sliding-autonomy helped seamlessly correct the error.

In summary, the standardized ADL task performance evaluation tool may help the clinicians or ARM suppliers to evaluate their training, prescription, or intervention more accurately and efficiently. It also helps ARM user interface researchers with a standardized tool to access performance and efficacy of developing user interfaces with the task-independent ISO 9241-9 throughput. To make the ARM user interfaces perform faster and errorless, the developed smartphone based touch-joystick manual user interface demonstrates improved performance and the sliding-autonomy framework showed on enhanced success rate without recalculating path planning and recognition.

6.2 LIMITATION AND FUTURE WORK

There are limitations to this study. A Hawthorne Effect is likely to appear for the first-time users. The Hawthorne Effect may be reduced with multiple trials. In addition, the individual learning pace and manipulation strategies may vary among trials. To eliminate the influence from the instructor, strategies for task completion were not limited. In the preliminary study, there were chances that the users got familiar or frustrated with the interface in the first two trials and decided to change to an inefficient strategy on the third trial. Therefore, we also used the minimal task completion time in three trials as a comparison.

In this study, due to the ARM is placed aside of users' wheelchairs, the robotic movement and planning are not influenced by the power seating functions or the wheelchair mobility. This might limit the manual manipulation strategies. The reason for this is that there require a significant amount of efforts and time. It can be resolved by either modifying the user's wheelchair and installing assistive interface or transferring and fitting the user to a single wheelchair which they are not familiar with. Either way would be inconvenient to the users. Therefore, this study focuses primarily on the assistance in the ARM manipulation. Moreover, in the current simulation model, the mobility of wheelchair seating functions and maneuverability were not taken into account. Future work may incorporate with the navigation and manipulation, so that more complex sequential task could be performed. Due to lack of environmental sensors, the robot had poor knowledge about surrounding situations. The PerMMA may be improved with the integration of more environmental sensors such as RGBD camera, or communication with surrounding electronic devices such as Beacon or Internet of Things (IoT). Although the assistive interface resolved the problems in the detection errors and the inaccuracy between simulated and real world environment, we still face the limitation of the task-driven autonomous function. Since the autonomous function is task-specific, an interface that users can quickly search and pick the correct task from a long task list is essential. In addition, user may need to intuitively assign appropriate TSR constraints for the CBiRRT. This interface may include the selection of task list, TSR constrain assignment, stop or re-start path planning, and switching between autonomous function and manual control. By combining IoT and the task list together, for example, once the PerMMA is driving into the kitchen, the refrigerator or oven reports their locations. The PerMMA then make several tasks that can do with the refrigerator or oven for the user to choose. In this way, the PreMMA filters out un-related tasks for the user. This study is limited to a lab setting, and not in the unstructured environment of the users' homes and communities. The tasks that the ARM user would do under different living areas may be different. To further explore this and construct a reasonable task list, an in-home ARM task logger would be necessary to monitor the daily ARM usage. Future studies may focus on monitoring the ARM usage at home and community, and improving the task selection of the assistive interface using machine learning algorithms.

For the future work of the ADL task board, one thing we have already started is the development of a modular ADL task board (Figure 37) with interchangeable task wireless modules so that we may evaluate more tasks on the same board. In addition, the current ADL task board did not consist bi-manual tasks because most objects on the vertical surfaces required only single ARM and most users only acquired one ARM. However, evaluation tool for bi-manual task is inevitable because most real life tasks are bi-manual, such as opening jars or boxes, cutting food, or charging phones. These current manual user interfaces might be able to complete these bi-manual tasks by operating each ARM independently. The future work may be to improve the assistive interface to complete the bi-manual tasks with synchronized motion. One potential way to open jars could be synchronized both ARMs' rotation so that the cap and the body of jar rotates in the opposite directions to accelerate the task. Another future study for the task board is to assess and gain feedback from the power wheelchair users in the preference of sliding-autonomy with the task board or bi-manual tasks. Moreover, although a previous study [32] has revealed a small difference from the starting locations affected by the dominant side of the ARM and we chose center as a convenient start location, it is not clear about how much would be affected with variant ADL task board orientation and location. For example, the right-handed JACO ARM may be easier to retrieve objects on the left side of the ARM. A similar effect was also found in the autonomous function of the left-handed iARM seemed more successful in grasping objects on its studied in the future.

Figure 37. The wireless interchangeable modular ADL task board

Overall, this work contributes several important parts of the ARM studies: 1) relation between performance evaluation and ADL task complexity; 2) normative data for first time users; 3) barriers and benefits of ARM UIs; 4) improvement on the touchscreen manual UI and sliding-autonomy. It also revealed limitations in current ARM studies such as lack of standardized ARM performance evaluation tools, systematic integration with previous studies, task-specificity of autonomous function and sliding-autonomy, and complexity of ADL task. Some future studies to overcome these limitations can be a modular ADL task board with bi-manual tasks, ADL task usage logger for home usage monitor, the customizable UI including BCI for broader populations with disabilities, incorporation of environmental sensors for the context awareness and more accurate PerMMA model for path planning for autonomous functions and sliding-autonomy.

APPENDIX A

QUESTIONNAIRE

The questionnaire was created using Google Live Form. It can be accessed online at https://docs.google.com/forms/d/1ig1HBWKoDfSnel69ATdvcmPcDN0ACAxYiB8_gbaWmlM/viewform.

Performance Evaluation of Task Board for Assistive Robotic Manipulators Questionnaire

* Required

Demographics

1. **User ID:** *

   ____

2. **Gender:** *

   Mark only one oval.

   - ( ) Female
   - ( ) Male

3. **Age:** *

   ____

4. **What is your highest level of education?** *

   Mark only one oval.

   - ( ) No formal education
   - ( ) Less than high school graduate
   - ( ) High school graduate/GED
   - ( ) Vocational training
   - ( ) Some college/Associate's degree
   - ( ) Bachelor's degree (BA, BS)
   - ( ) Master's degree (or other post-graduate training)
   - ( ) Doctoral degree (PhD, MD, EdD, DDS, JD, etc.)

5. **Do you consider yourself Hispanic or Latino?** *

   Mark only one oval.

   - ( ) Yes
   - ( ) No

6. **If “Yes”, would you describe yourself:**
Mark only one oval.

- Cuban
- Mexican
- Puerto Rican
- Other: ____________________

7. **How would you describe your primary racial group?**
Mark only one oval.

- No primary group
- White Caucasian
- Black/African American
- Asian
- American Indian/Alaska Native
- Native Hawaiian/Pacific Islander
- Multi-racial
- Other: ____________________

8. **Are you a veteran?**
Mark only one oval.

- Yes
- No

Health Information

9. **In general, would you say your health is:**
Mark only one oval per row.

	Poor	Fair	Good	Very good	Excellent
	◯	◯	◯	◯	◯

10. **How often do health problems stand in the way of you doing the things you want to do?**
Mark only one oval per row.

	Never	Seldom	Sometimes	Often	Always
	◯	◯	◯	◯	◯

11. **Are you limited in any way in any activities because of physical, mental, or emotional problems?**
Mark only one oval.

- Yes
- No
- Don’t know/not sure
- Refused

12. **Do you now have any health problem that requires you to use special equipment, such as a cane, a wheelchair, a special bed, or a special telephone?**
Mark only one oval.

- Yes
- No
- Don’t know/not sure
- Refused

13. **Do you have any health problem that results in you needing help from another person on a daily basis?**
Mark only one oval.

- Yes
- No
- Don’t know/not sure
- Refused

14. **(If yes) Do you need help with… (Check all that apply)**
Check all that apply.

- [ ] bathing
- [ ] dressing
- [ ] grooming (e.g., shaving, brushing teeth)
- [ ] feeding yourself
- [ ] taking medications
- [ ] completing other treatments (e.g., exercise, speech therapy, special diet)
- [ ] transferring in and out of bed or chair
- [ ] walking
- [ ] preparing meals
- [ ] cleaning
- [ ] shopping
- [ ] transportation
- [ ] Other: ____________________

For each of the following items, please check the statement that best describes you. Do not check more than one box in each group.

15. **Mobility**
Mark only one oval.

- I have no problems getting about
- I have some problems getting about
- I am confined to bed

16. **Self-care**
Mark only one oval.

- I have no problems with self-care
- I have some problems washing or dressing myself
- I am unable to wash or dress myself

17. **Usual activities (e.g. work, study, housework, family or leisure activities)**
Mark only one oval.

- I have no problems with performing my usual activities
- I have some problems with performing my usual activities
- I am unable to perform my usual activities

18. **Pain/discomfort**
Mark only one oval.

- I have no pain or discomfort
- I have moderate pain or discomfort
- I have extreme pain or discomfort

19. **Anxiety/Depression**
Mark only one oval.

- I am not anxious or depressed
- I am moderately anxious or depressed
- I am extremely anxious or depressed

20. **For each of the following conditions please indicate if you have ever had that condition in your life, have the condition now at this time, or never had the condition. Check one box for each condition.**
Mark only one oval per row.

	In your lifetime	Now	Never
Amputation			
Arthritis			
Asthma or Bronchitis			
Cancer (other than skin cancer)			
Cerebral Palsy			
Diabetes			
Epilepsy			
Heart Disease			
Hearing Impairment			
Hypertension			
Multiple Sclerosis			
Muscular Dystrophy			
Post Polio Syndrome			
Spina Bifida			
Spinal Cord Injury			
Stroke			
Traumatic Brain Injury/Closed Head Injury			
Vision Impairment			
Upper extremity impairment (e.g., reaching, grasping, holding things, using computer mouse, etc.)			
Other significant illnesses (please list)			

21. **Other illnesses**

General Technology Attitudes / Efficacy

The following questions are about your attitudes and views towards assistive robotic manipulators in general. In general, to what extent do you believe that technology… (check one box for each item)

22. **Makes life easy and convenient**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all											Completely

23. **Makes life complicated**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all											Completely

24. **Gives people control over their daily lives**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all											Completely

25. **Makes people dependent**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all											Completely

26. **Makes life comfortable**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all											Completely

27. **Makes life stressful**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all											Completely

28. **Brings people together**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all											Completely

29. **Makes people isolated**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely

30. **Increases personal safety and security**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely

Factors Related to Technology Adoption in General

If you were considering using an assistive robotic manipulator to assist you with important daily tasks, how important would each of the following factors be to you in deciding whether or not to use it? (check one box for each item)

31. **How well it meets your needs**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not important at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely important

32. **Ease of use**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not important at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely important

33. **Cost**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not important at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely important

34. **The way it looks (attractiveness)**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not important at all											Extremely important

35. **How visible it is to others**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not important at all											Extremely important

36. **How safe it is to use**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not important at all											Extremely important

Select the first robotic manipulator

37. **The 1st wheelchair-mounted robotic manipulator is ...** *
Mark only one oval.

- iARM *Skip to question 49.*
- JACO ARM *Skip to question 38.*

Factors Related to Uptake of JACO Arm – BASELINE ASSESSMENT

Based on what you know now, how well do you think each of the following statements describe this technology? Please rate how accurate you think each is in describing this specific technology application (check one box for each item).

38. **Learning to use JACO will be easy for me**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

39. **It will be easy to get JACO to do what I want it to do**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely accurate

40. **I am anxious about using JACO**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely accurate

41. **It will be confusing for me use JACO correctly**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely accurate

42. **Using JACO will make my life easier**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely accurate

43. **Using JACO will help me to achieve important goals**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely accurate

44. **It would be easier to just get another person to help rather than using JACO**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

45. **JACO is attractive from a physical standpoint**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

46. **It will be embarrassing to be seen using JACO**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

47. **The benefits JACO will provide are worth the cost of the device**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

Skip to question 59.

Select the second robotic manipulator or the last page of questionnaire

48. **Select the 2nd robot or the last page of questionnaire** *
Mark only one oval.

- ⬭ JACO ARM *Skip to question 38.*
- ⬭ iARM *Skip to question 49.*
- ⬭ Last Page of Questionnaire *Skip to question 99.*

Factors Related to Uptake of iArm – BASELINE ASSESSMENT

Based on what you know now, how well do you think each of the following statements describe this technology? Please rate how accurate you think each is in describing this specific technology application (check one box for each item).

49. **Learning to use iARM will be easy for me**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

50. **It will be easy to get iARM to do what I want it to do**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

51. **I am anxious about using iARM**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

52. **It will be confusing for me use iARM correctly**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

53. **Using iARM will make my life easier**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

54. **Using iARM will help me to achieve important goals**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

55. **It would be easier to just get another person to help rather than using iARM**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

56. **iARM is attractive from a physical standpoint**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

57. **It will be embarrassing to be seen using iARM**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

58. **The benefits iARM will provide are worth the cost of the device**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

Skip to question 79.

Factors Related to Uptake of JACO – FOLLOW-UP ASSESSMENT

Please rate how accurate you think each is in describing this specific technology application (check one box for each item).

59. **Learning to use JACO was easy for me**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

60. **It was easy to get JACO to do what I want it to do**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

61. **I am anxious about using JACO**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

62. **It is confusing for me to use JACO correctly**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

63. **Using JACO would make my life easier**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

64. **Using JACO would help me to achieve important goals**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

65. **It would be easier to just get another person to help rather than using JACO**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

66. **JACO is attractive from a physical standpoint**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

67. **It would be embarrassing to be seen using JACO**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

68. **JACO sometimes doesn't work properly**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

69. **JACO seems too flimsy, like it might break**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

70. **If JACO needs repairs, I could probably fix it myself**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

71. **I couldn't afford to get JACO fixed if it broke**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

72. **It would be difficult to move JACO if I needed to have it somewhere else**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

73. **It would be easy to take JACO with me wherever I need it**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

74. **I would worry about someone stealing JACO**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

75. **JACO is just as good as newer things on the market**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

76. **I would prefer that a caregiver assist me in operating JACO remotely**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

77. **I would prefer to operate JACO independently**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

78. **I would prefer that a caregiver operate JACO for me remotely**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

Skip to question 48.

Factors Related to Uptake of iArm – FOLLOW-UP ASSESSMENT

Please rate how accurate you think each is in describing this specific technology application (check one box for each item).

79. **Learning to use iARM was easy for me**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

80. **It was easy to get iARM to do what I want it to do**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

81. **I am anxious about using iARM**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

82. **It is confusing for me to use iARM correctly**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

83. **Using iARM would make my life easier**

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

84. **Using iARM would help me to achieve important goals**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

85. **It would be easier to just get another person to help rather than using iARM**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

86. **iARM is attractive from a physical standpoint**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

87. **It would be embarrassing to be seen using iARM**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

88. **iARM sometimes doesn't work properly**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

89. **iARM seems too flimsy, like it might break**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

90. **If iARM needs repairs, I could probably fix it myself**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

91. **I couldn't afford to get iARM fixed if it broke**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

92. **It would be difficult to move iARM if I needed to have it somewhere else**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

93. **It would be easy to take iARM with me wherever I need it**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all											Extremely accurate

94. **I would worry about someone stealing iARM**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

95. **iARM is just as good as newer things on the market**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

96. **I would prefer that a caregiver assist me in operating iARM remotely**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

97. **I would prefer to operate iARM independently**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

98. **I would prefer that a caregiver operate iARM for me remotely**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not accurate at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely accurate

Skip to question 48.

Final page of Questionnaire

99. **In general, do you think Assistive Robotic Manipulators would:**
Mark only one oval.

- Make your life better
- Make your life worse
- Wouldn't make much difference

100. **Where and in what situations would it be helpful for people with disabilities to use assistive robotic manipulator?**

....
....
....
....
....

101. **In what places and situations would you be willing to use assistive robotic manipulator?**

....
....
....
....
....

102. **In what places and situations would you not be willing to use assistive robotic manipulator?**

....
....
....
....
....

103. **In addition to the way you have used assistive robotic manipulator today, can you think of other ways that it might be used in everyday life?**

....
....
....
....
....

104. **What do you like best about assistive robotic manipulators? Please explain your answer**

105. **What do you like least about assistive robotic manipulators? Please explain your answer**

106. **If you were in charge of redesigning assistive robotic manipulator, what would you do differently? Please explain your answer**

End of Questionnaire

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APPENDIX B

QUICKDASH

The QuickDASH questionnaire has a PDF version (http://dash.iwh.on.ca/conditions-use), an Excel version (http://dash.iwh.on.ca/scoring), and the online version used in this work at http://www.orthopaedicscore.com/scorepages/disabilities_of_arm_shoulder_hand_score_quickdash.html.

*Quick*DASH

Please rate your ability to do the following activities in the last week by circling the number below the appropriate response.

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. Open a tight or new jar.	1	2	3	4	5
2. Do heavy household chores (e.g., wash walls, floors).	1	2	3	4	5
3. Carry a shopping bag or briefcase.	1	2	3	4	5
4. Wash your back.	1	2	3	4	5
5. Use a knife to cut food.	1	2	3	4	5
6. Recreational activities in which you take some force or impact through your arm, shoulder or hand (e.g., golf, hammering, tennis, etc.).	1	2	3	4	5

	NOT AT ALL	SLIGHTLY	MODERATELY	QUITE A BIT	EXTREMELY
7. During the past week, *to what extent* has your arm, shoulder or hand problem interfered with your normal social activities with family, friends, neighbours or groups?	1	2	3	4	5

	NOT LIMITED AT ALL	SLIGHTLY LIMITED	MODERATELY LIMITED	VERY LIMITED	UNABLE
8. During the past week, were you limited in your work or other regular daily activities as a result of your arm, shoulder or hand problem?	1	2	3	4	5

Please rate the severity of the following symptoms in the last week. *(circle number)*	NONE	MILD	MODERATE	SEVERE	EXTREME
9. Arm, shoulder or hand pain.	1	2	3	4	5
10. Tingling (pins and needles) in your arm, shoulder or hand.	1	2	3	4	5

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	SO MUCH DIFFICULTY THAT I CAN'T SLEEP
11. During the past week, how much difficulty have you had sleeping because of the pain in your arm, shoulder or hand? *(circle number)*	1	2	3	4	5

***Quick*DASH DISABILITY/SYMPTOM SCORE** = $\left(\left[\frac{\text{sum of n responses}}{n}\right] - 1\right) \times 25$, where n is equal to the number of completed responses.

A *Quick*DASH score may not be calculated if there is greater than 1 missing item.

APPENDIX C

ADAPTED WOLF MOTOR FUNCTION TEST

The original Wolf Motor Function Test [48] was not designed for assistive robotic manipulators (ARM). Therefore, to adapt the capability of the ARMs and target population, some subtests are not included or modified. For example, the folding towel subtest requires bimanual movement that is not capable because there is only one ARM present in the task. Another example is that the power wheelchair users rarely use pencils and paperclips due to the loss of hand function. Therefore, the subtests of picking up a pencil and paperclips are changed to moth sticks and keys with adaptor that is more common to their daily objects. Here are the subtests used in this study.

1. Hand to table (front)
2. Hand to box (front)
3. Weight to box
4. Lift can to mouth
5. Lift mouth stick
6. Lift Key with adaptor
7. Turn key in lock with key adaptor
8. Lift basket

Adapted Wolf Motor Function Test Data Record Form for the Assistive Robotic Manipulator

User ID:
Date:

Subtests	Time for JACO arm (s)	Functional Ability	Time for iARM (s)	Functional Ability
Hand to table (front)		0 1 2 3 4 5		0 1 2 3 4 5
Hand to box (front)		0 1 2 3 4 5		0 1 2 3 4 5
Weight to box		0 1 2 3 4 5		0 1 2 3 4 5
Lift can to mouth		0 1 2 3 4 5		0 1 2 3 4 5
Lift mouth stick		0 1 2 3 4 5		0 1 2 3 4 5
Lift Key with adaptor		0 1 2 3 4 5		0 1 2 3 4 5
Turn key in lock with key adaptor		0 1 2 3 4 5		0 1 2 3 4 5
Lift basket		0 1 2 3 4 5		0 1 2 3 4 5

Functional Ability Scale

0 – Does not attempt with assistive robotic manipulator being tested.
1 –Assistive robotic manipulator being tested does not participate functionally; however, attempt is made to use the robotic manipulator.
2 – Does, but requires assistance of the assistive robotic manipulator not being tested for minor readjustments or change of position, or requires more than two attempts to complete, or accomplishes very slowly.
3 – Does, but movement is influenced to some degree by synergy or is performed slowly or with effort.
4 – Does; movement is close to normal *, but slightly slower; may lack precision, fine coordination or fluidity.
5 – Does; movement appears to be normal *.
(*) For the determination of normal, the less pause time can be utilized as an available index for comparison, with pre-morbid upper extremity dominance taken into consideration.

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