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Performance evaluation of The Personal Mobility and Manipulation Appliance (PerMMA)

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ABSTRACT

The Personal Mobility and Manipulation Appliance (PerMMA) is a recently developed personal assistance robot created to provide people with severe physical disabilities enhanced assistance in both mobility and manipulation. PerMMA aims to improve functional independence when a personal care attendant is not available on site. PerMMA integrates both a smart powered wheelchair and two dexterous robotic arms to assist its users in completing essential mobility and manipulation tasks during basic and instrumental activities of daily living (ADL). Two user interfaces were developed: a local control interface and a remote operator controller. This paper reports on the evaluation of PerMMA with end users completing basic ADL tasks. Participants with both lower and upper extremity impairments ($N = 15$) were recruited to operate PerMMA and complete up to five ADL tasks in a single session of no more than two hours (to avoid fatigue or frustration of the participants). The performance of PerMMA was evaluated by participants completing ADL tasks with two different control modes: local mode and cooperative control. The users' task completion performance and answers on pre/post-evaluation questionnaires demonstrated not only the ease in learning and usefulness of PerMMA, but also their attitudes toward assistance from advanced technology like PerMMA. As a part of the iterative development process, results of this work will serve as supporting evidence to identify design criteria and other areas for improvement of PerMMA.

1. Introduction

According to 2009 statistics, the highest percentage (6.9%) of the more than 36 million Americans with disabilities indicated their disability was related to "ambulation", while the next most prevalent (5.4%) disability was related to "independent living." [1]. These statistics demonstrate the growing needs for experienced personal care attendants (PCA) by persons with disabilities. However, due to the increasing unavailability and cost of experienced PCAs, the rapidly-growing needs for more personal assistance in this population are unmet [2]. When an on-site professional PCA is not available, a persistent demand exists for quality alternative assistance. Assistance robots have emerged as a tool to provide enhanced assistance to people with impairments in completing activities of daily living (ADL) by utilizing advanced robotic technologies and computer intelligence, i.e., "smart technology." Technology that aids in these tasks should be designed to allow users to live independently and safely by allowing them to manipulate their natural environments either independently or through assisted-control mobility [3]. According to a literature review study, the number of people with disabilities in the United States who could benefit from using a wheelchair-mounted robotic manipulator is estimated at most to be 150,000, which is 0.06% of the population [4].

Robotic arms have advanced in the past two decades to allow people with upper extremity impairment or amputation to resume partial or full capability of completing manipulation tasks in their daily lives [5]. A survey study by Prior showed that 84% of power wheelchair users would purchase a robotic arm if it were available [6]. An early example of a manipulation assistance system utilizing robot arms is the Desktop Vocational Assistant Robot (DeVAR) [7], which consists of a small robotic arm mounted on an overhead track system above a desk which is controlled using discrete word voice commands. The ASIBOT, with 6 degrees of freedom (DoF) and a universal docking socket at both ends, allows either end to function as the fixed point or the gripper [8]. The "My Spoon" meal assistance device developed by SECOM Co. Ltd., is designed to allow persons with little upper extremity function to feed themselves

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independently. The "My Spoon" device allows the person with impairment to eat along with the caregiver and/or family members [9].

There are also mobile robots with manipulators. The Care-O-bot 3 is an interactive mobile butler that has been under development to assist with daily tasks (http://www.care-o-bot.de/Produktblaetter/PB_300_309e.pdf). Moving safely in everyday environments and among humans, the Care-O-bot 3 is able to detect and grasp typical household objects (http://www.care-o-bot.de/english/). More specifically, the Care-O-bot 3 can autonomously plan and follow an optimal path to a given destination while avoiding both dynamic and static obstacles [10]. The Care-O-bot 3 has tactile sensors in each finger allowing the robot to adjust its grasping force [11]. The rob@work is a prototype intelligent assistant with a commercial manipulating arm. The rob@work robot can assist with retrieving and carrying, assembly, and tool handling tasks, and is based on the same mobile platform used in the Care-O-bot (http://www.care-o-bot.de/english/RobAtWork.php). The PR-2 Robot is a mobile robot designed for home or work use that is able to move around obstacles in its environment. It has back-drivable arms, and wrists with two continuous degrees of freedom and enough torque to manipulate everyday objects (http://www.willowgarage.com/pages/pr2/overview).

Many facilities have conducted research studies to evaluate user experience and different interfaces so that wheelchair users may perform object manipulation independently and efficiently. Several wheelchair mounted assistive robotic arms (WMRA) have also been developed, evaluated, and commercialized recently. An early prototype is the Raptor arm which, mounted on the right side of a wheelchair [12], has four DoF and a two-fingered gripper, moves by joint reconfigurations, and has no feedback or preprogramming capability [13]. Evaluation of Raptor's effects on the independence of people with disabilities has been conducted with 12 participants, and significant ($p < 0.05$) improvements were found in 7 of 16 ADLs. These improved tasks included pouring of drinking liquids, picking up straws or keys, accessing the refrigerator and telephone, and placing a can on a low surface [14]. One of the most commonly investigated robotic arms in rehabilitation research is the commercially available Manus Assistive Robot Manipulator (ARM) [15]. The Manus ARM is a seven DoF robotic arm with two-fingered hand. It can be controlled by keypad, joystick, or single-button switches [16]. New user interfaces, and the ability to switch between controller modes, were developed for use with the ARM to reduce the physical and cognitive load on the user [17]. Additional control interfaces have also been developed for the ARM including a PDA device [18]. A specific purpose robotic arm, the DORA, has been developed for door opening tasks only [19]. The JACO arm (http://kinova.force.com/KinovaEn?key=homepage&lang=en) is a robotic manipulator which is composed of six inter-linked segments with a three-fingered hand. The hand can grasp objects using either two or three fingers. It can be controlled by its own 3DoF joystick [20].

Different user interfaces have been evaluated for these WMRAs such as joysticks and keypads [14,16,17,20,21], as well as vision-based interfaces [4,19,22–25]. Most studies focus on the automation of grasping objects to ease the user's cognitive workload and increase efficiency. However, studies show that users report less acceptance if the manipulator is entirely automatic. There is a trade-off between the workload put on users and the computational load on the robot (http://www.physorg.com/news204482386.html). Though many studies follow the concept of user-centered design or "consumer in the loop" design, best practices would be not only to interact with the real end-user, but also the extended users such as family members, PCA, and others who would influence the usage of the new technologies.

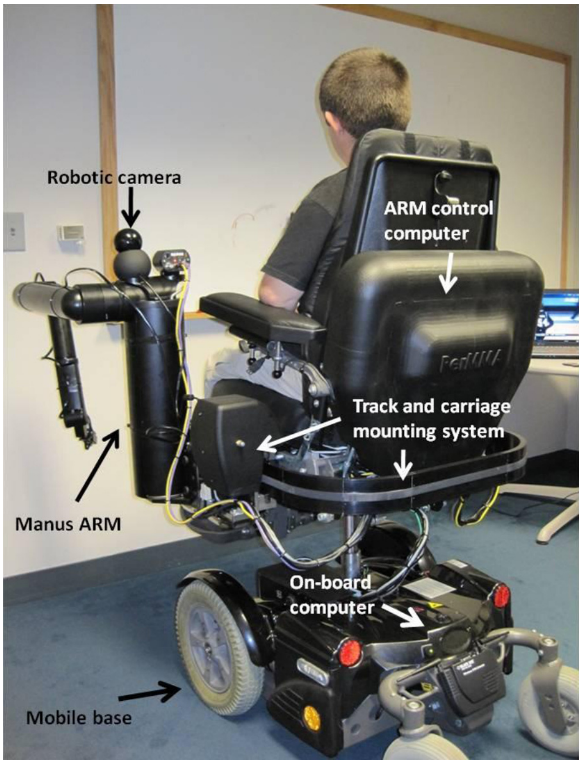

Fig. 1. PerMMA system overview.

The Personal Mobility and Manipulation Appliance (PerMMA) is a new personal assistive robot, composed of a robotic powered wheelchair [26] and two Manus ARMs to provide enhanced mobility and bimanual manipulation to people with lower and upper extremity impairment (LUEI) [27]. The purpose of the PerMMA project is to develop a robotic system that provides mobility and manipulation assistance to people with disabilities, with the practical aim of increasing independence and expanding function. This paper reports on the evaluation of PerMMA with end users when performing ADL tasks.

2. Methods

2.1. PerMMA system descriptions

Efficiently combining mobility with manipulation and actively involving end users in completing their daily living tasks should result in significant improvements in the quality of life of people with LUEI. The design and development of the PerMMA system hardware and software has been presented in a previous study [27]. PerMMA (see Fig. 1) includes.

2.1.1. Mobility

PerMMA uses a PerMobil® C500 EPW (PerMobil Inc., USA) as its mobile base so that the robustness and reliability of movement is assured. The C500 EPW provides a maximal payload capacity of 120 kg. It includes four powered seating functions, seat back recline, seat tilt, elevating legrests, and seat elevation. All original equipped manufacturer (OEM) electronics were removed and replaced with customized devices for integrating advanced features, such as manipulation and sensing.

2.1.2. Manipulation

Two Manus Assistive Robot Manipulators (Exact Dynamics Inc., The Netherland)-so-called ARMs – were selected for PerMMA's

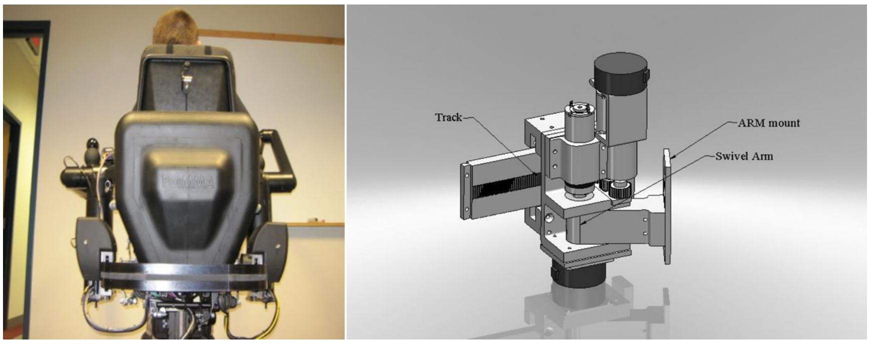

Fig. 2. PerMMA track and carriage system (left: real system on chair; right: solid model).

manipulation capabilities. Each Manus ARM has a 6 DoF arm and a two-fingered gripper, and has a maximal reach radius of 830 mm around its shoulder and a vertical reach range from −385 mm to 1275 mm with respect to its base. Each ARM is capable of lifting a payload up to 2.5 kg when the arm is not outstretched.

2.1.3. Sensing

A variety of sensors are integrated into PerMMA to provide real-time feedback during its operation in order to enhance PerMMA's intelligence as well as safety. A web camera with tilt and pan control is mounted on the shoulder of each Manus ARM to provide vision feedback for the remote operator. A Bluetooth® microphone is included to allow local users to communicate with remote operators. Wi-Fi and 3G accessibility are also integrated into PerMMA, which allows the system to communicate with computers and devices in the environment, and other computers in remote locations.

2.1.4. Integration

In order to integrate the ARMs with the mobile base, a custom track and carriage system was designed and developed, as shown in Fig. 2. This novel track and carriage system allows the two arms to move anywhere along the mobile base, and previous work of ours has shown that this novel track-and-carriage mounting system increased the workspace and manipulability of PerMMA by over 50 percent compared to the classic fixed mounting design [28]. The cameras and sensors are instrumented without interfering with the use of both the arms and the wheelchair base.

2.1.5. User interfaces

Two different user interfaces were developed. The OEM joystick of the C500 EPW and two EPW seating function control boxes (Fig. 3) were adapted as the local control interface for mobility and seating functions, since most of PerMMA's users use EPW as their primary means of mobility and are familiar with these devices. A touchpad (IntelliTools, USA, Fig. 3) was chosen to be the control interface for the two arms. Customized layouts were designed to accommodate the varied range of motion and strength of the users' upper limbs. Each layout contains 16 keys, whose sizes (small or big buttons) and locations (left-handed or right-handed) were designed based on users' preferences. Among these 16 keys, seven pairs are colored and labeled for the control of the Manus ARM's 6 joints and grippers. A "SWITCH" key allows the user to select between the left and right arm, and a "STOP" key stops all motions of the active ARM. Sensitivities of the touchpad and the icons on the printed layout can be easily modified for users with different physical and cognitive capabilities.

A remote operation station (Fig. 4) was developed to allow a family member or a caregiver to remotely operate PerMMA if the user's motor or cognitive functions are too limited to independently complete those tasks when on-site assistance is not available. The remote operator uses an OEM computer keyboard to remotely control the driving speed and direction of the base, and uses two Phantom Omni haptic joysticks (SensAble Technologies Inc., USA) to control movements of both Manus ARMs. The similar physical structure of the haptic joystick and the Manus ARM makes manipulation more intuitive, easy to learn, and predictable for the remote operator. Each haptic joystick provides 6 DoFs, and each of them is mapped to control one DoF of the Manus ARM.

2.2. Control modes

Due to the complexity of controlling PerMMA's 22 DoFs, multiple control modes have been designed: local user (LU) mode, remote user (RU) mode, and cooperative control mode.

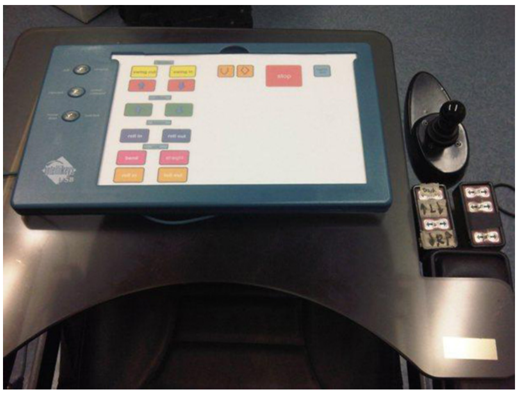

Fig. 3. PerMMA's local interface.

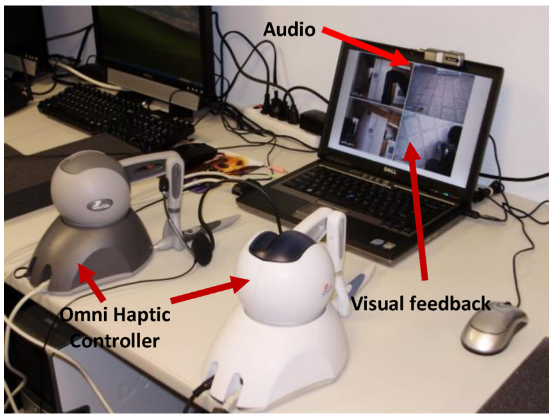

Fig. 4. PerMMA's remote operation interface.

2.2.1. LU mode

In LU mode, the local user has full control of PerMMA. The user can drive PerMMA using the wheelchair joystick, adjust the seat using all four control box seating functions, relocate both ARMs along the track using a track control box, and operate both ARMs with the touchpad.

2.2.2. RU mode

In RU mode, a remote operator can drive the base using a standard personal computer keyboard, control seating functions and track motions using either keyboard or voice command, and operate both ARMs using either the haptic joysticks or the keyboard. The keyboard-based manipulation control is the same as the local user has in local mode. With the haptic joysticks, the remote operator is able to control both ARMs simultaneously to perform complex bimanual manipulations. Each joint of a joystick controls a joint of the ARM, and a fuzzy control algorithm was developed to control the ARM to track the reference input from the joystick.

2.2.3. Cooperative mode

In cooperative mode, the local user and a remote operator work together to complete mobility and manipulation tasks. The local user decides which function that he or she wishes to delegate to the remote assistant. Commonly the local user drives PerMMA, controls seating functions and handles the track motions using the local control interface, while the remote operator operates both ARMs with the remote operation interface to perform bimanual manipulations. The local user remains in command of the process, leaving the remote operator the role of a subordinate activator. The remote operator utilizes the two cameras to look at and locate an object. The local user also provides audio feedback to the remote operator so that he/she can obtain a better perception of the environment. Both of them provide communicate with each other through a wireless network or cellular phone connection in order to better coordinate mobility and manipulation to complete tasks.

2.2.4. Safety features

PerMMA has three levels of features aimed at mitigating risk of injury to the occupant. First, the software level includes soft stops by pushing a button on keyboard and keypad; keep-out zones to protect the local user from colliding with the arms; and a limited maximum speed of the mobile base and movement of arms. Second, the mechanical and electronic level includes a clean and neat design; sharp edges, hidden wires and moving parts have also been removed or covered. Third, the system level includes an independent cut-off switch available for the local user to shut off power to the whole system. The arms are designed to slowly collapse during a power outage, thus a hard stop will be safe even the arms are loaded. The details of the safe features are presented in [27].

2.3. Subjects

Participants were recruited at the Center for Assistive Technology, University of Pittsburgh. The inclusion criteria are: (1) age 18 years or older, (2) have lower extremity impairment and use an EPW as their primary means of mobility, (3) have concomitant injury or disease affecting at least one upper extremity, (4) sitting tolerance of 6 h or greater, (5) ability to understand and follow multi-step instruction, (6) ability to travel to the laboratory for testing purposes. The exclusion criteria are: (1) presence of an active pressure ulcer, (2) body mass greater than 113 kg, which is the limit of the seating system, (3) need for a seat width greater than 0.46 m or a seat depth less than 0.41 m. Subjects were recruited from the Center for Assistive Technology at the University of Pittsburgh and the registered user database of the Human Engineering Research Laboratories.

Table 1
Pre/post-evaluation questionnaire.

Q1	Learning to use PerMMA will be/was easy for me
Q2	It will be/was easy to get PerMMA to do what I want it to do
Q3	It will be/was confusing for me to use PerMMA correctly
Q4	Using PerMMA will/could make my life easier
Q5	Using PerMMA will/could help me to achieve important goals
Q6	It will/could be easier to just get another person to help rather than using PerMMA
Q7	It will be/is embarrassing to be seen using PerMMA
Q8	Using PerMMA will be/is an invasion of my privacy
Q9	The benefits PerMMA will provide are worth the cost of the device

2.4. Test protocol

All evaluations were conducted in a controlled environment at the Activities of Daily Living Laboratory (ADLL) of the Human Engineering Research Laboratories (HERL). The study protocol was approved by the Institutional Review Board (IRB) of the University of Pittsburgh. Each participant completed a single session of less than 2 h and could pause or quit the evaluation whenever he/she thought the physical or cognitive load was too much to continue.

After discussing and signing the consent form, each participant was given instructions on PerMMA before they transferred to PerMMA. A demonstration of how to operate PerMMA with both local and cooperative control interfaces was also presented to the participant. The demonstration was up to half an hour long. After the instruction, each participant was asked to complete a pre-evaluation questionnaire including questions regarding the control interface evaluation (Table 1), which assessed the participant's impression of PerMMA after the instruction and demonstration. All questions were answered with a score from 0 (not at all) to 10 (extremely). After completing the questionnaire, participants transferred from their own mobility devices to PerMMA. Each participant was asked to practice freely for at least 15 min, including driving, moving the ARMs along the track, and manipulating objects.

Five basic but frequently used ADL tasks were selected for the evaluation based on the previous focus group studies and clinical experiences: (T1) retrieve a piece of tissue from a tissue box on a desk. The task was complete when the user successfully placed the tissue in his/her hand, (T2) pick up a meal container with a flexible handle from a desk and put it down at a predefined new location. The task was complete when the user successfully relocated the container to the required location, (T3) open a microwave oven by pushing the door button. The task was complete when the user successfully opened the door of the microwave oven, (T4) retrieve a plastic cup and move it close enough for the user to drink. The task was complete when the user successfully moved the cup close enough to his/her mouth for drinking or placed the cup in his/her hand, (T5) retrieve a straw and put it into a plastic cup, and pick up the cup and move it close enough for the user to drink with the straw. This task was complete when the user successfully moved the cup, with the straw inside it, close enough to his/her mouth to drink with the straw. These tasks were designed to represent essential ADL tasks (or subcomponents of them) frequently needed in one's independent living, and cover different requirements in range of motion and dexterity of manipulation such as grabbing and relocating objects (T1, T2, T4, T5), applying force to an object (T3), moving an object very close to one's body (T1, T4, T5), fine alignment of the arm and the object (T2, T3, T5), and manipulation that may involve bimanual behaviors (T5). The order of the tasks

Table 2
Unique questions in post-evaluation questionnaire.

Q10	I would prefer that a caregiver assist me in operating PerMMA remotely
Q11	I would prefer to operate PerMMA independently
Q12	I would prefer that a caregiver operate PerMMA for me remotely

Table 3
Number of participants who complete each task with both control interfaces.

	T1	T2	T3	T4	T5
Local	13	12	8	3	3
Coop	15	13	9	3	3

was counterbalanced. The participant started each task from a predefined starting location 2 m away from the targeted objective.

The local mode and the cooperative mode were chosen to be used in the evaluation. There are two reasons: users prefer the system not be controlled completely by a remote operator, and to minimize potential risks of the study and always keep the participant as an active controller in the testing. The participant first completed all tasks with local mode using the local control interface, and then completed the same tasks in the same sequence with cooperative mode. A HERL researcher using the remote operation center served as the remote operator that cooperated with the local user. Although both the local user and remote operator were in the same room to maximize safety, the remote operator always used the remote operation center to control PerMMA and for feedback. The amount of time used for completing each task was recorded. An assistive technology professional (ATP) was onsite throughout all tasks and held a safety switch to be able to completely shut down PerMMA if potential risks were observed. After performing all attempted tasks, each participant was asked to complete a post-evaluation questionnaire, which included the same questions Q1–Q9 as in the pre-evaluation questionnaire (Table 1) and some unique questions Q10–Q12 (Table 2). The post-evaluation questionnaire evaluated not only the participant's experience after using PerMMA, but also their attitudes and preferences on PerMMA.

3. Results

Fifteen participants (9 male and 6 female, age 42.9 ± 15.8 years) completed the evaluation. All participants had both lower and upper extremity impairments and use powered wheelchairs as their primary mean of mobility: 5 of them had spinal cord injury, 5 of them had cerebral palsy, 3 of them had muscular dystrophy, 1 of them had a traumatic brain injury, and 1 of them had congenital impairments. Limited by their different levels of ability and the length of each session, not all participants completed all five tasks. The numbers of participants who completed each task are shown in Table 3.

The means and standard deviations of the time used for completing each task with both control interfaces are shown in Table 4.

Table 6
Scores of Q10–Q13 of the post-evaluation questionnaire (range: 0–10).

	Q10	Q11	Q12
Post-evaluation	4.5 ± 3.3	8.7 ± 2.6	3.3 ± 2.8

The means and stand deviations of the scores to questions Q1–Q9 are shown in Table 5. The mean and stand deviation values of the scores to questions (Q10–Q12) are shown in Table 6.

4. Discussion

Although none of the participants were able to complete all five tasks within a single session due to the limited time and their different types and levels of disabilities, six of them successfully completed four tasks, two of them completed three tasks, three of them completed two tasks, and one of them completed one task, all with both control modes. Participant 6 successfully completed two tasks (T1 and T2) with the local control mode, and completed three tasks (T1, T2 and T3) using the cooperative mode. Participants 2 and 15 failed to complete any tasks using the local control mode because they could not precisely point and push the buttons on the touchpad due to upper extremity spasticity, which identified a limitation of the current local mode. However, participant 2 successfully completed T1 and T2 with the cooperative mode, and participant 15 successfully completed T1 with the cooperative mode.

The cooperative control mode greatly reduced the time used for completing each task compared with the local control interface, as shown in Table 4. There are several reasons for this improvement. One reason is the difference between the local and remote operation interfaces. With the haptic joysticks, the remote operator is able to simultaneously control all joints of both Manus ARMs. However, the local interface can only control one ARM at a time and the local user has to switch between different ARMs during the task. The remote operator had been practicing on the remote operation station for hours before the evaluation, while the local user only had 15–30 min of practice and only used PerMMA for less than 2 h. Significant difference was found in the performance of task T1 ($p = 0.0004$), T2 ($p = 0.0011$), and T4 ($p = 0.01$). No significant difference was found in the performance of task T3 ($p = 0.0537$) and T5 ($p = 0.1966$). These results indicated that for manipulating objects without the requirement of fine alignment of the arm and the object, the remote operator could do significantly faster than local user (T1, T2, and T4). However, when fine adjustments were required, due to the lack of 3 dimensional visions of the objects and environment, there might be longer time needed for remote operator to complete the operation.

The overlapped pre/post-evaluation questionnaire results showed the ease of learning PerMMA, the usefulness of PerMMA in real tasks, and the user's attitudes and preferences about advanced assistive devices like PerMMA. The participants thought PerMMA

Table 4
Time used for completing each task (unit: second).

	T1	T2	T3	T4	T5
Local	350.2 ± 194.8	296.5 ± 156.9	192.4 ± 151.5	275.7 ± 44.1	418.0 ± 306.5
Coop	136.4 ± 60.1	123.9 ± 48.9	70.0 ± 31.4	70.3 ± 12.0	220.0 ± 140.3

Table 5
Scores of Q1–Q9 of the pre/post-evaluation questionnaire (range: 0–10).

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
Pre-evaluation	7.5 ± 1.7	6.3 ± 1.5	3.7 ± 3.2	6.3 ± 2.6	6.4 ± 2.6	3.7 ± 2.5	3.7 ± 2.7	3.2 ± 3.1	7.0 ± 2.0
Post-evaluation	7.0 ± 2.7	5.5 ± 2.7	5.0 ± 3.5	6.9 ± 3.0	7.2 ± 3.0	5.6 ± 3.1	3.0 ± 2.8	3.1 ± 3.2	6.1 ± 2.4

would be easy before they tried it (7.5 ± 1.7) and, after trying PerMMA in person and completing the evaluation, participants mostly agreed that PerMMA was easy for them to learn (7.0 ± 2.7). A majority (10 out of 15, 66.7%) indicated in the post-evaluation questionnaire that PerMMA was as easy as or even easier to use than their initial impression. No significant difference was found in the pre/post-evaluation scores of this question (Q1) ($p = 0.527$). 9 out of 15 participants (60.0%) indicated in the post-evaluation questionnaire that it was as easy as or easier to get PerMMA to do what they wanted it to do than their initial impression. Although the score dropped from 6.3 ± 1.5 to 5.5 ± 2.7, no significant difference was found ($p = 0.33$) (Q2). Post-evaluation, the participants thought it was a little more confusing for them to use PerMMA correctly (5.0 ± 3.5) than their initial impression when they watched the demonstration (3.7 ± 3.2) (Q3). The main reason for this may be that it was the first time the participant saw and used PerMMA and they did not have enough training and practice. The participants thought that PerMMA could make their life easier (Pre: 6.3 ± 2.6, Post: 6.9 ± 3.0) (Q4), and that PerMMA could help them to achieve important goals (Pre: 6.4 ± 2.6, Post: 7.2 ± 3.0) (Q5).

Four participants (26.7%) raised their score and eight participants (53.3%) gave the same score to Q6: that it could be easier to just get another person to help rather than use PerMMA. There was a significant increase in the score (Pre: 3.7 ± 2.5, Post: 5.6 ± 3.1, $p = 0.008$) and seven participants thought that getting another person to help would be easier than using PerMMA by giving a score higher than 5. One reason for this may be that most participants were accustomed to traditional personal assistance, and using PerMMA was new to them. Another reason may be the lack of training and practice using PerMMA. Some users felt a little frustrated when they failed to memorize the functions of all keys or failed to generate correct motions. Most participants did not think that using PerMMA would be embarrassing (Pre: 3.7 ± 2.7, Post: 3.0 ± 2.8) (Q7), and did not consider using PerMMA to be an invasion of their privacy (Pre: 3.2 ± 3.1, Post: 3.1 ± 3.2) (Q8). The participants thought that PerMMA would provide benefits that were worth its cost (Pre: 7.0 ± 2.0, Post: 6.1 ± 2.4) (Q9).

The three unique questions in the post-evaluation questionnaire evaluated the participants' preferences on the cooperative control for completing ADL tasks in their daily living and how they would like PerMMA to assist them. A majority of participants (12 out of 15, 80.0%) preferred to operate PerMMA independently to complete tasks, and 10 participants scored 10 points to this question (8.7 ± 2.6). Cooperatively working with a caregiver to complete tasks together got the second highest score (4.5 ± 3.3), and letting a caregiver operate PerMMA remotely was the least preferred (3.3 ± 2.8). This shows that although most participants accepted the cooperative mode – which led to significantly improved performance in the evaluation – most of the participants preferred to regain their independence and complete ADL tasks by themselves. This result validates PerMMA's cooperative control concept, which is designed to maximize the user's independence and, at the same time, provide on-demand assistance whenever the user asks for it.

There are some limitations of this study. First, there was limited time in each session. The study was designed to be a single session of less than 2 h in order to minimize potential fatigue or frustration of the participant. However, this time limit also restricted the activities of participants. No participant was able to try all five tasks in the limited time, and only six participants were able to try four tasks. Second, the order for using two modes to conduct the experiments was not randomized, therefore there were order effects. In future studies, the mode order should be randomized. The last limitation of this study was the participants' lack of training. The participants only had about 30 min to learn and practice how to operate PerMMA. Although all of them started the evaluation with real tasks after they thought they were ready to use PerMMA, some of them still had trouble controlling PerMMA properly and needed reminding and assistance from the ATP. In future studies, a multiple session design will be employed to allow participants to use PerMMA for multiple hours.

5. Conclusion and future work

This paper reported and discussed the evaluation of a newly developed personal assistive robot, the PerMMA, for people with LUEI. Fifteen subjects were tested. Each participant tested PerMMA with two modes, the local mode and the cooperative mode. Thirteen subjects successfully completed at least one task with both modes. Two subjects failed to complete any tasks with the local mode due to their disabilities, but successfully completed at least one task with the cooperative mode. The cooperative mode reduced the time that a subject spent to complete a task, and significant differences were found in three of the five tasks. Results of the questionnaire showed that the majority of the participants thought PerMMA was easy to learn and easy to use. However, further development of standardized language and methods for training on the use of PerMMA is planned and will take into account a variety of different learning styles to maximize its potential use. The participants also thought PerMMA would make their life easier and that using PerMMA in their daily lives would not be embarrassing or cause any invasion of their privacy. Although participants accepted cooperative control with a caregiver, a majority of them preferred to operate PerMMA independently. As a part of the iterative development, results of this study can be used as supporting evidence to identify design criteria for future improvement of PerMMA.

In our future work, we will investigate the relation between characteristics of the users' disabilities and their performance, and improve the accessibility of PerMMA's control interfaces based on the findings in this study. A voice control interface and a touch screen interface are being developed and will be evaluated by future studies.

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Ethical approval

The study protocol was approved by the Institutional Review Board (IRB) of the University of Pittsburgh. IRB number is PRO08120433.

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Conflict of interests

None declared.

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