LITERATURE REVIEW OF WHEELCHAIR-MOUNTED ROBOTIC MANIPULATION: USER INTERFACE AND END-USER EVALUATION

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INTRODUCTION AND BACKGROUND

In the past two decades, nearly a dozen of wheelchair mounted assistive robotic manipulators (WMRM) have been developed, evaluated, and commercialized. In addition, many facilities have conducted research studies to evaluate user experience and different interfaces so that wheelchair users may perform object manipulation independently and efficiently. However, despite of these attempts, there are only few options available on the market currently.

According to the most recent studies, the number of people with disabilities in the United States who could be benefit from using a wheelchair mounted robotic manipulator is estimated at most to be 150,000, which is 0.06% of the population. This population includes people with muscular dystrophy, spinal cord injury, spinal muscular atrophy, multiple sclerosis, amyotrophic lateral sclerosis, cerebral palsy, rheumatoid arthritis, postpolio syndrome, locked-in syndrome, and other severe motor paralysis (Laffont et al., 2009). Also, the number of people in the United States over age of sixty-five will double from 34.7 million to 69.4 million by 2030 (Haigh & Yanco, 2002). As these people begin to show degenerative symptoms, needs of assistance in object manipulation will increase.

Commercialization success for WMRM depends upon reliability, cost-efficiency, appearance, functionality, and usability. Reliability and cost-efficiency are factors that can be defined and evaluated by design requirements. However, the appearance, functionality, and usability of WMRM require applying the concept of user-centered design. User-centered design is defining and evaluating design requirements with the participation of end-users. The goal of functionality is to duplicate the functionality of a human's arm. Most WMRMs have seven degrees of freedom (DOF) including gripper, which is the same DOF as human upper extremities (if neglecting fine finger movement). . Usability, including the user interface and vision-based automation, isdesigned to facilitate the users in accomplishing certain type of tasks (Stanger, Anglin, Harwin, & Romilly, 1994).

The main purpose of this review article is to provide quantitative and qualitative evaluation measurements for current commercialized WMRMs while developing new user interfaces. The findings will not only help researchers identify appropriate tools for evaluating WMRM performance, but also help physicians and therapists to use proper assessment methods.

METHOD

Scientific and medical databases such as PubMed, Google Scholar, and the University of Pittsburgh Library System-PITTCat were searched. The papers included in the review articles that were found spanned from 1989 to 2011. The keywords used for searching included: wheelchair mounted; rehabilitation robotics; manus arm; JACO arm; iARM; clinical evaluation; wheelchair; robotic; manipulator; upper limb; upper extremity; disability. Both forward and backward search strategies were used to find related references.

RESULTS

Twenty studies were selected as having direct relevance to the study objective. They were separated into three broad categories: commercialized wheelchair mounted robotic manipulators, developing user interfaces, and evaluation measurements. Due to limited space a subset of articles in each category are discussed in more detail below.

DISCUSSION

Commercialized Wheelchair Mounted Robotic Manipulators

Two commercialized WMRMs were selected because they are the most common on the market: Manus ARM and JACO manipulator.

The Manus ARM (Assistive Robotic Manipulator) is a seven DOF robotic arm with two-fingered hand manufactured by Exact Dynamics, which also manufactures an updated version called iARM. It can be controlled by keypad, joystick, or single-button switches (Römer, Stuyt, Peters, & van Woerden, 2004).

The JACO manipulator, manufactured by Kinova Technology, 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 (Kinova; Maheu, Archambault, Frappier, & Routhier, 2011).

Table 1: Specification Comparison of Two Common Commercialized Wheelchair Mounted Robotic Manipulator

	iARM	*JACO*
Manufacturer	Exact Dynamics	Kinova Technology
Weight	9kg	5kg
Weight limit	1.5kg	1.5kg (45cm) 1.0kg (90cm)
Reach	90cm+20cm (lift unit)	90cm
Max speed	15cm/sec	15cm/sec
Degree of Freedom (DOF)	7 incl. gripper 8 with lift unit	7 incl. gripper
Hand	2 fingers	3 fingers
Finger force	20N	7N
Control possibilities	Keypad, Joystick, Single buttons, sip & puff, chin control	Special 3 DOF joystick, joystick, gamepad
Power	24VDC/3A(max.)	24VDC/1.5A

In summary, the iARM has more possibilities in its user interface and a higher gripping force. However, the JACO manipulator has a lighter weight with one more finger, which provides more dexterity in grasping.

Developing User Interface and Clinical Evaluation Measurements

A survey study of users' activity of daily living (ADL) task priorities shows that the task with the highest priorities is picking up objects from the floor or shelf (Stanger, et al., 1994). Moderately high priorities are eating/drinking, preparing food/drinks, and personal hygiene. Based on these survey results, the manipulation of objects on the floor or shelf became the most evaluated task in the following studies.

Joysticks and keypads are the common user interfaces of WMRM. 6 participants with Duchenne muscular dystrophy were recruited for using WMRM for 6-72 months. The time of daily usage and average reduced caregiving time were reported. A survey of frequency of daily tasks shows frequent WMRM usage in eating and using remote controls (Bach, Zeelenberg, & Winter, 1990).

A study was performed with 11 spinal cord injury wheelchair users who performed 16 ADLs using a Raptor arm, a WMRM with 3 DOF. Task completion time with dependency classifications were recorded without WMRM, after initial training, and after 13 hours of use (Chaves, Koontz, Garber, Cooper, & Williams, 2003).

A study (Römer, et al., 2004) using Manus ARM compared 13 long-term (>4 years) Manus ARM users with 21 non-ARM users who have similar levels of impairment. ADL tasks and assistance time were recorded. It showed that the ARM users perform 40% more ADL tasks than the other group. The Manus ARM was used about 2 hours on average daily.

Another usage study (Romer, Stuyt, & Peters, 2005) using Manus ARM quantified the daily usage and reduced caregiving time with 8 non-Manus-ARM users for 12 months. Users were observed for one week every three months to record caregiver assistant time and manipulator usage duration. The Manus ARM was used 0.6-3.7 hours daily with a reduced assistance time of 0.7-1.8 hours.

A study by TNO and Delft University evaluated their own graphical user interface for Manus ARM with 4 powered wheelchair users with weak upper limb strength. The measurements included the number of mode switches, task time, Rating Scale of Mental Effort (RSME), and interviews (Tijsma, Liefhebber, & Herder, 2005).

The JACO manipulator is controlled by a special 3 DOF joystick, which adds the third DOF of twisting the joystick knob in conjunction with the keypad on the controller to select control modes. A study was conducted with 27 powered wheelchair users who performed 6 tasks twice of grasping objects and pouring water using a JACO manipulator mounted on the tabletop (Francois Routhier, 2010). Performance was evaluated by number of trials, perceived easiness, and an important survey. Another study in which 31 wheelchair users participated was also conducted using similar measurements (Maheu, et al., 2011).

Voice control can be used for users who have difficulty with manipulating a joystick or keypad. A study of 24 high-level quadriplegics from Palo Alto Veterans Affairs Spinal Cord Injury Center evaluated a desktop vocational assistant robotic workstation. Subjects were asked to prepare a meal, feed themselves, wash their face, shave, and brush their teeth. Measurements of performance were recorded with in-house designed pre- and post-task questionnaires, interviews, and observer assessments (Hammel et al., 1989).

A vsion-based interface transfers the loading in positioning and fine adjustment to the computer on the wheelchair. Task completion time can be reduced with increased efficiency. 10 users with SCI evaluated a UCF-Manus ARM by performing pick-and-place tasks . This vision-based manipulator was controlled in either manual or autonomous mode. Performance was evaluated by task completion time, number of commends, task completion rate, and Psychosocial Impact of Assistive Devices Scale (PIADS) which were measured before, during, and after study (Kim & Behal, 2009; Kim et al.).

Another vision-based study was conducted with 12 wheelchair users with Traumatic Brain Injury, CP, and Spina Bifida for 15 weeks of performing pick-and-place task using a Manus ARM. Measurement for performance included completion time, successful trial rate, level of attention, level of prompting, PIADS, and surveys about improvement (K. Tsui & Yanco, 2007; K. M. Tsui, Kim, Behal, Kontak, & Yanco, 2011; K. M. Tsui, Yanco, Feil-Seifer, & Matariƒá, 2008).

A panoramic camera was used in a study different from the previous two (Laffont, et al., 2009) to evaluate a graphic user interface using a Manus ARM to perform a task of grasping pre-defined objects scattered within the robot's workspace. 20 people with disabilities were recruited as an intervention group in comparison with 24 able-bodied in a control group. Performance was measured by task duration, percentage of panoramic camera use, number of clicks, and with user satisfaction questionnaires.

Table 2: Evaluating measurements

User Interface	*Measurements*	*Reference*
Joystick and keypad	Time of daily usage Caregiving time ADL Completion time Frequency of ADL Number of trials Interview Number of mode switch RSME	(Bach, et al., 1990; Chaves, et al., 2003; Francois Routhier, 2010; Maheu, et al., 2011; Römer, et al., 2004; Romer, et al., 2005; Tijsma, et al., 2005)
Voice control	Pre/Post questionnaire Interview Observer assessments	(Hammel, et al., 1989)
Vision based	Task completion time Task completion rate Number of clicks PIADS User satisfaction	(Kim & Behal, 2009; Kim, et al.; Laffont, et al., 2009; K. Tsui & Yanco, 2007; K. M. Tsui, et al., 2011; K. M. Tsui, et al., 2008)

Task completion time is the most commonly used measurement for all the interfaces. This measurement may show the improvement compared to not using WMRMs. However, it may not be able to specifically reflect deficiency in the movement. For example, if two tasks have the same completion time but one is reported difficult and the other is easy, this accumulated measure would not be enough for researchers to determine which part makes the task difficult. Moreover, there is a need for developing clinical evaluation and assessment protocols as well as larger interaction with insurance companies or healthcare economists (Mahoney, 1997).

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 technologies. WMRM may interact with tangible objects most of the time; however, intangible interaction with these users and discussion of topics such as social aspect or aesthetics would give researchers broader point of views for their design (Harwin, Rahman, & Foulds, 1995).

Most studies focus on the automation of grasping objects to ease the user's cognitive workload and increase efficiency. However, studies ("Robotic arm's big flaw: Patients say it's 'too easy'," 2010) show that users report less acceptance if the manipulator is entirely automatic. There is a trade-off between workload put on users and computational load on the robot.

CONCLUSION

Although technological development has made WMRMs more efficient and easier to use, there is still lots of room to improve. One major improvement would be to develop a two-way interaction between higher dexterity WMRMs and fewer DOF from end-users. Vision- based interfaces with autonomous path planning would tremendously reduce user problems with adjusting to the correct grasping position. It would also reduce the required DOF for picking and putting tasks since only few clicks can finish the job. However, it would also take away user involvement.

Another improvement could be developing clinical protocols and measurements for quantitatively and qualitatively evaluating task efficiency and performance. Currently, there are not enough measurements in common for different research to be quantitatively comparable. Development in this area would help physicians and therapists in assessing and prescribing WMRMs.

Future development in easy but slightly challenging interfaces, along with improved quantitative and qualitative evaluation, will maximize the independence in ADL of WMRM users.

ACKNOWLEDGEMENTS

This material is based upon work supported by Quality of Life Technology Engineering Research Center, National Science Foundation (Grant #0540865). The contents of this paper do not represent the views of the Department of Veterans Affairs or the United States Government.

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