

Selection Considerations and a Comparison of Commercial Wheelchair Mounted Robotic Arms

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ABSTRACT

Primary users of powered mobility, typically also have upper extremity limitations that impede their ability to perform activities of daily living (ADLs). A wheelchair mounted robotic arm (WMRA) offers the user an option to perform these tasks and become more independent, which makes it essential that the device is effective and efficient. In this paper, three important aspects were studied to help the WMRA designers have a standardized method of evaluation of performance as well as considerations clinicians should look for when prescribing these devices to different individuals with disabilities. These three aspects are: Kinematical analysis to assess the space constraints, user interface & control (evaluation) to determine user acceptance, and WMRA selection criteria.

Keywords

Wheelchair, Robotic, Arm, Selection, Evaluation.

1. INTRODUCTION

Proper design and function of WMRA are critical points and should encompass ease of use, reduced cognitive load, etc. Conversely, poor design may result in frustration and decreased independence. Unlike other assistive technology, there are limited data and evaluation protocols developed for WMRA selection and utilization.

This study investigates the usability of wheelchair mounted robotic arms (WMRA) through kinematic analysis and evaluation of different aspects related to WMRA design, user interface systems and selection criteria. The US Census Bureau [5] showed that one of every five Americans had difficulty performing functional activities (about 53 million). Among these, half (over 26 million) were considered to have severe disabilities. In the case of spinal injury, robotic arm aids are most appropriate for individuals with C-5 - C-6 or higher level injuries. Individuals that require mobility assist devices, such as a power wheelchair, can benefit from various robotic devices because the power wheelchair provides a platform with which to mount the device and supply power to it. An important design consideration of where to mount a robotic arm in a power wheelchair is the safety of the operator. There have been several attempts in the past to create commercially viable wheelchair mounted robotic arms, including Manus and Raptor. Manus utilizes a front mounting location beside the operator's knee [2], while Raptor mounts to the side of the wheelchair below the armrest [3].

2. METHODOLOGY AND ANALYSIS

2.1 Kinematic Analysis

A workspace was chosen based on Hillman et al [4], which reflects specific requirements of individuals with disabilities. Horizontal and vertical planes were chosen to create a mesh of points in space that represent the user's workspace. Figure 1 shows the selected planes in all directions. A concept known as the "manipulability ellipsoid" [6], which is commonly used in robotics literature is the volume of the ellipsoid that represents the work space of the end effector. Manipulability is defined as the determinant of the Jacobian matrix (J) of the positional sub-matrix of the final transformation matrix of the manipulators arm reference frame.

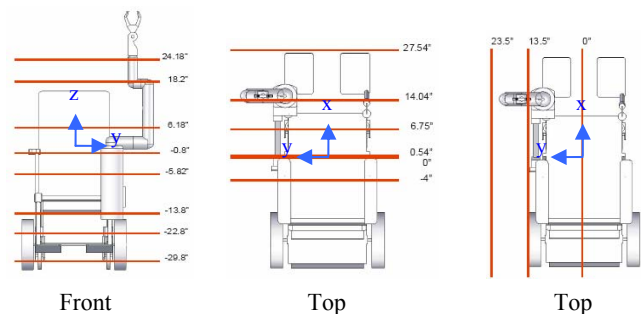


Figure 1. Workspace: Horizontal and vertical planes.

SolidWorks was used to determine the joint angles of each robot arm in order to find the manipulability measure and to verify it within the solid model. The Jacobian matrix was derived from the D-H parameters using the appropriate formulae [1]. Figure 2 shows the frames of reference for the power wheelchair, Manus and Raptor respectively.

The inverse kinematics of the robotic arms was determined using MatLAB to calculate the joint angles of the robotic arm for a given point in 3-D space. In order to create a procedure for the Kinematic analysis of WMRA, it is necessary to separate the process into a series of steps as follows: After creating a D-H parameter table and transformation matrices for the manipulator to be measured, link transformations for the manipulator were calculated, and hence, the Jacobian matrix was developed. Then, the manipulator and a generic power wheelchair were modeled in Solid Works so that the joint angles and gripper relationships can be shown graphically. A series of points (grids) surrounding the wheelchair / arm assembly were specified according to specific

applications in rehabilitation engineering. A computer program was created using numerical methods approach to determine the joint angles of the arm for a given point in the workspace (inverse kinematics). The joint angles were then used to determine the manipulability of the arm for the given point.

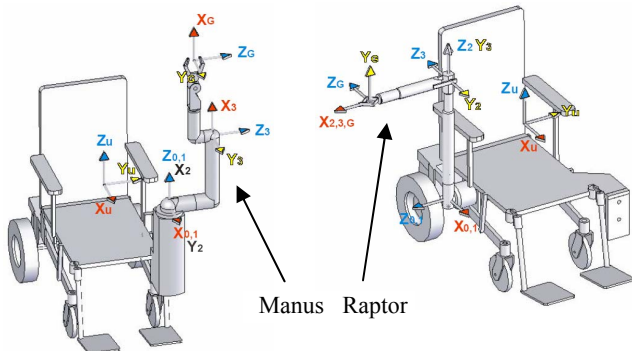


Figure 2. Reference frames.

Values for the manipulability measure were plotted in both horizontal and vertical planes. In order for a point in the workspace to be defined as accessible, it must have a manipulability measure of at least 100 [6]. A method for representing the relative value of the normalized manipulability measure (nmm) and a qualitative determination are shown in figure 3. The size and color of the spheres are used to represent the manipulability measure as a percentage of the maximum manipulability measure computed.



Figure 3. Manipulability measure.

Figure 4 and figure 5 show a sample of the normalized manipulability measures (nmm) of the Manus and Raptor respectively within the defined workspace.

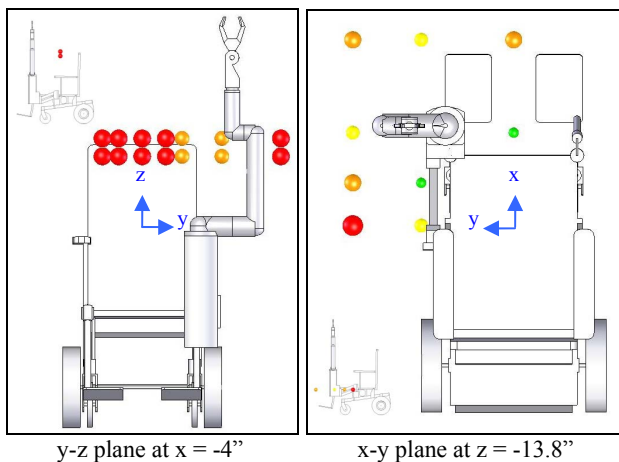


Figure 4. Manipulability measure sample for MANUS.

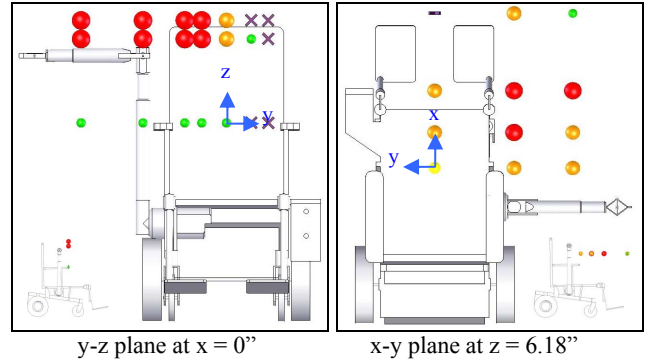


Figure 5. Manipulability measure sample for Raptor.

It is interesting to note that regions where the arm traditionally has lower manipulability measures are the areas that have the highest measures at $z = -29.8''$. Table 1 shows a summary of the effectiveness in reaching areas common to activities of daily living (ADL) for both Manus and Raptor.

Table 1. Comparison between Manus and Raptor effectiveness.

Category	Manus		Raptor	
	nmm*	Rating	nmm*	Rating
Pick-up off ground	0.33	Limited	0.57	Good
Coffee table	0.57	Good	0.55	Good
Door knob	0.53	Good	0.59	Good
Kitchen countertop	0.54	Good	0.54	Good
Light switch	0.65	Very Good	0.35	Limited
Low kitchen shelf	0.64	Very Good	0.05	Very Limited
Reach into lap	0.57	Good	0.31	Limited
Access to mouth	0.81	Excellent	0.55	Good

*nmm is the normalized manipulability measure.

The qualitative assessment is based on the average of the normalized manipulability measure of all possible wheelchair orientations possible to accomplish the task. Six possible qualitative assessments could be given for each task.

2.2 User Interface and Control (Evaluation)

Based on the results from the Kinematic Analysis, a test bed was designed to evaluate the user interface and control of each WMRA. In order to assess the functional use, different ADL related tasks (figure 6) were designed as follows:

- Relocating an object on a level plane: This task consisted of moving the WMRA from the home position (H), picking up an object from quadrant-1 and positioning it in quadrant-2. Each quadrant was 8" deep and 11.5" wide. The quadrants were on a table surface 30" above the floor surface.
- A pronation / supination function to simulate a pouring function: This task consisted of moving the WMRA from the home position (H), picking up a water bottle from quadrant-1 and pouring the water into a cup in quadrant-2. Each quadrant was 11.5" deep and 8" wide.
- Accessing a higher level cabinet: This task consisted of moving the WMRA from the home position (H), picking up the

object from the surface of a shelf (24") above the surface of the table and placing it on the table surface.

(d) Picking up an object from the floor: This task consisted of moving the WMRA from the home position (H) to the floor (1), picking up the object and placing it on the table surface (2).

Two individuals with disabilities (C5-6 quadriplegia) of similar size and weight, who are power wheelchair users for 25 years were selected to test the evaluation test bed. The home position for each WMRA was chosen as the stored position in which the user would normally place the arm when traveling. After each user was trained on the use of the WMRA device, they were timed on the performance of each task. Errors were noted if the object was dropped, placed 6" beyond the destination or task was incomplete. In the second phase, cognitive load was added to determine the effect on the time. This was done by asking the subjects a series of questions using a telephone headset as they performed each task.

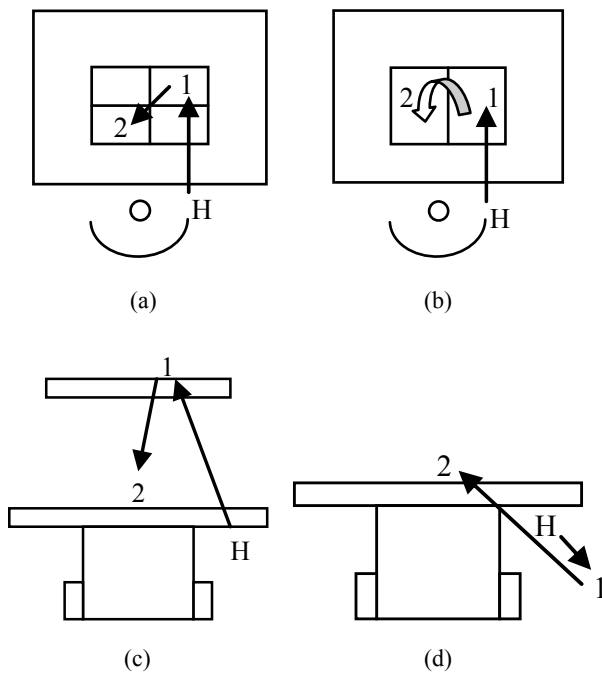


Figure 6. Four different ADL tasks.

Each task was performed three times and the time was recorded. The Raptor was tested with the joystick interface and the Manus with the joystick and the keypad interfaces. The input device for Raptor consists of an eight-way joystick. An additional set of switches controlled the opening and closing of the gripper. The four-way joystick of Manus controls the arm and the gripper using four different menus in the Cartesian control mode. The user accesses the menus by a quick tap of the joystick in either direction. The keypad interface consists of 16 buttons that the user can activate for control of the WMRA. Both the keypad and joystick systems offered a visual display to the user indicating the menu and function.

The tests showed that the Raptor control interface was the easiest to understand and learn. However the users found it difficult to activate the secondary switch for opening and closing the gripper. The Manus with joystick was the most difficult to learn and errors

were caused by the user when using the joystick to access the menu structure. The keypad offered direct control and was most efficient. However the users had difficulty with the size of the buttons and shape on the keypad.

In moving the object in the same plane, the users had difficulty picking up objects from quadrant 1 and took an average of 180 seconds to pick up the object using Raptor. Once the object was picked up, positioning it in quadrant two was done in 15-30 seconds and the return to home occurred in 20 seconds or less. The same task took about half the time when Manus was used with the keypad. Cognitive loading interestingly did not affect the initial phase of the task (H-1), but significantly increased the time by three times for the remainder of the task. The users had difficulty with diagonal movement of the arms.

The pouring task was the most difficult and the operation of tilting the bottle often caused the water to spill outside the receiving cup when Raptor was used. The model presented was a useful test to evaluate the WMRAs. Both the degrees of freedom and the control interface are critical for an efficient WMRA. Performance was best in the case of the Manus with the keypad, where sufficient degrees of freedom existed with the least complicated control. However, the performance can be greatly enhanced by a more intuitive control with less cognitive load.

2.3 WMRA Selection Criteria

The following factors need to be considered when selecting a WMRA:

- a) Wheelchair Specifications: As the weight and dimensions of the wheelchair are increased, the balance and handling of the wheelchair are affected. Narrow doorways and vehicle lifts are a problem. The Manus has a feature that allows it to be quickly disconnected. Although this cannot be performed by the user, it is necessary especially in transportation.
- b) Degrees of Freedom: The increased degrees of freedom increase the efficiency of the arm to perform tasks such as drinking, pouring and orientation.
- c) User interface and control: In the tests conducted by this study, since the users were active power wheelchair users, they favored a joystick interface, but did not like using a two dimensional control for three dimensional output. A space-ball or glove with voice recognition and macro controls would be far more efficient.
- d) Nature of disability: A WMRA would be most beneficial to C-5 or higher quadriplegics and individuals with CP as well as progressive disabilities. Careful consideration needs to be made regarding the cognitive and visual concentration necessary for effective control.
- e) Weight and shape of objects: The objects in this study primarily consisted of round surfaces, although square objects were also used during the training. Smooth round surfaces were difficult to hold securely if the gripper is not properly oriented, and Manus has the advantage of more DOF in this aspect.
- f) Types of tasks: It is critical for a clinician to note the tasks that the user intends to do with the WMRA. This will help

design training that will enable the user to become proficient with the use of the device.

3. CONCLUSIONS

WMRAs offer the ability for many individuals with severe mobility and manipulation disabilities to participate in various activities. There are a limited number of products on the market and improvements are necessary in the user interface. Controls need to take into account human factors principles and provide a more efficient way to produce the desired direction and function. A 4 DOF arm, such as the Raptor, represents the bare minimum to be useable at all. The first three joints provide position control, leaving only one joint to control orientation. This wrist joint must rotate in the main axis of the forearm, which is detrimental to manipulability. The Manus has 6 degrees of freedom, allowing full position and orientation control. This is the primary reason for it's better manipulability scores.

Controller design is a vital consideration when designing a complete robotic manipulator system. Significant gains for robotic manipulators in rehabilitation applications will come from advanced controllers and user interfaces for easy programming and operation.

Further research is necessary to evaluate the function of the WMRAs in an objective and useful method. This paper provides a model that can be used for this purpose that is closely aligned with

typical tasks that users would want to do. Specific selection criteria are presented based on consumer input that can be used to develop a viable protocol for prescribing WMRA devices. Conducting the studies in a motion analysis lab with the tasks presented b is planned to compare the kinematics in real time.

4. REFERENCES

- [1] Craig, J., 2003, "Introduction to robotics mechanics and control", third edition, Addison- Wesley Publishing, ISBN 0201543613
- [2] Eftiring, H., Boschian, K., "Technical results from manus user trials", *Proc. ICORR '99*, 136-141, 1999.
- [3] Hillman, M., Gammie, A., "The Bath institute of medical engineering assistive robot", *Proc. ICORR '94*, 211-212, 1994.
- [4] Hillman, M., Hagan, K., Hagan, S., Jepson, J., and Orppwood, R., 1999, "A wheelchair mounted assistive robot", *Proc. ICORR '99*, pp. 86-91.
- [5] US Census Bureau (1997), "Disabilities affect one-fifth of all americans," *Census Brief* , CENBR/97-5, December 1997, <http://www.census.gov/prod/3/97pubs/cenbr975.pdf>
- [6] Yoshikawa, T., 1985, "Manipulability of robotic mechanisms", *International Journal of Robotics Research*, 4(2), pp. 3-9.