FEASIBILITY ANALYSIS OF DAILY ACTIVITIES USING ASSISTIVE ROBOTIC MANIPULATORS

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ABSTRACT

In the United States, more than 21.5 million people report a limitation in their self-care activities and independent living. Assistive robotic manipulators (ARMs) can provide assistance with daily tasks for people with upper extremity impairments. Previous studies have evaluated ARM efficacy in completing single and multiple action tasks. This paper presents the feasibility analysis of two sequential daily self-care activities, brushing teeth and preparing and then eating a simple meal. The two tasks were successfully completed by a well-trained investigator using the ARM. By analyzing the difficulties and failures in the testing, the ARM's kinematic and dynamic limitations and the kinesthetic perceptions made it difficult to re-adjust motion planning before errors occurred. In addition, we provide an example to alleviate environmental limitations. Due to the differences between the ARM and human motions, some intuitive human motion plans were not applicable to the ARM motion. The results of this work may help researchers and clinicians develop appropriate accessories, make adequate environmental adjustments, and tailor training for ARM users.

BACKGROUND

In the United States, more than 21.5 million people report limitations in the self-care activities and independent living (Erickson, Lee, & von Schrader, 2014), such as dressing and eating and doing errands alone. In addition, a growing older adult population with moderate to severe disabilities is estimated to reach 24.6 million people in 2040 (Johnson, 2007). Assistive robot manipulators (ARMs) have emerged as a tool to assist with activities of daily living (ADLs) (Allin, Eckel, Markham, & Brewer, 2010). Commercial ARMs such as iARM by the Exact Dynamics (Dindom, The Netherlands) and JACO by Kinova (Montreal, Canada), were developed to assist people with upper extremity impairments with manipulation tasks in their daily living and increase their independence (Driessen, Evers, & Van Woerden, 2001; Maheu, Archambault, Frappier, & Routhier, 2011).

The adaptation of new assistive technologies requires not only a solid understanding of the interface but also new ways in performing tasks. For example, a new power wheelchair user has to learn not only the joystick control interface but also develop new strategies to move around places due to the limitation of the mobility device. Similarly, better ARM performance relies on both the efficient control interface and fluid motion planning. Studies evaluated the ARM control efficiency using various levels of ADL tasks: single action, multiple actions, and sequential tasks (Chung, Wang, & Cooper, 2013), shown in Table 1. These studies evaluated ARM performance using single or multiple action tasks, such as pick-and-place and pushing buttons and evaluated users' abilities with different control interfaces. However, most ADL tasks are sequential, which are the combinations of successful completion of single and multiple actions in a suitable sequence. A complete eating sequence includes not only scooping of food and placing a spoon in the mouth but also applying different motion plans to collect food from different locations in the bowl.

Table 1. Tasks for ARM performance evaluation in previous studies (Chung, Wang, & Cooper, 2013).

Evaluation Variables	Single Action	Multiple Actions	Sequential Task
Fitts Parameter **Completion Time** **Number of Clicks/ Commands**	Press buttons Turn knob/key Push door handle Pick & place Pick up pens Stack blocks Block & Box Minnesota Test Peg-in-hole	Wolf Motor Function Test Jebsen Hand Test Retrieve tissue Drinking	Meal preparation Eating
Success Rate **Perceived Difficulty** **Average Daily Usage** **Interviews**	Lift objects Shave	Draw lines Feed pets Page turning	Meal preparation Eating Operate device Pour water Wash face/teeth

Several studies (Chung, Hannan, Wang, Kelleher, & Cooper, 2014; Chung, Wang, Kelleher, & Cooper, 2013) were conducted to evaluate the ARM efficacy with standardized performance evaluation tools that can minimize environmental variability so that performance from different studies can be easily contrasted or compared. These studies revealed statistical differences in the efficacy of ARM performance across tasks. Noticeably, better performance on the standardized tools may lead to less errors and faster performance in the sequential tasks. However, most ARM studies were evaluated in lab settings. The feasibility using common objects within ordinary environments remains to be determined. Additionally, few studies have reported the limitations and challenges of ARM performance under real life situations.

Thus, in this study, we assessed the feasibility of two sequential self-care tasks, brushing teeth and preparing and then eating a simple meal. Successful motion planning in conjunction with the limitations and challenges under real life situations were examined to help researchers and clinicians develop appropriate accessories and make adequate environmental adjustments for ARM users.

PURPOSE

The purpose of this study was to explore the following research questions.

1. Is the ARM capable of completing the two ADL tasks within a natural environment?
2. What are the challenges or limitations while completing these ADL tasks?

METHOD

Sequential Tasks

The sequential tasks were selected from the Self-Care and Domestic Life sections in the International Classification of Functioning (ICF) (World Health Organization, 2001). The ICF provides evaluation of body functions and ADLs, which is usually utilized for the examination of assistive technology. Brushing teeth (d5201) and preparing (d6300) and then eating a simple meal (d550) were the two sequential tasks assessed in the study. The sequence of the brushing teeth task is listed in the Table 2 and 3. In the brushing teeth task, the brush and toothpaste were initially placed in a cup next to the sink (Figure 1 left). For the eating task, the food was initially placed in a microwavable container in the refrigerator. The investigator had to microwave the food then eat it (Figure 1 right).

Figure 1. Two sequential tasks (Left: brushing teeth, Right: preparing and then having a simple meal)

Testing Equipment and Environment

In this study, a right-handed JACO ARM mounted on the right side of a C500 Permobil power wheelchair was used for testing. A joystick JACO ARM controller is mounted on the right side of the power wheelchair, next to the wheelchair joystick. The JACO joystick controller was set as 3-axis mode. The sequential tasks were performed in the kitchen environment at the Human Engineering Research Laboratories (HERL), University of Pittsburgh. The kitchen includes a sink with a faucet, a microwave, and a refrigerator (Figure 1). The objects used in the testing were a regular toothbrush, toothpaste, cup, and spoon. However, the cover of the microwavable container is too small for the ARM to open. Therefore, we used an adapted container used in the previous study (Wang et al., 2013), which has handles attached to the container and cover.

Evaluation Protocol

One of the investigators in the study performed the two sequential tasks. The investigator (4 years ARM experience) was trained following the JACO training manual. After training, the investigator was evaluated the familiarity of control interface using the ADL task board (Chung, Wang, Kelleher, et al., 2013). The ADL task board is a standardized tool to accurately assess the ARM performance of an indicator invariant of tasks and environments, throughput (TP) from the ISO 9241-9 standard, Requirements and Performance Testing for non-keyboard input devices (Douglas, Kirkpatrick, & MacKenzie, 1999) using six daily objects: big button, elevator button, light switch, toggle switch, door handle, and knob. The investigator then performed the two tasks following the sequence list in Table 2 and 3. The investigator rated the difficulty after completion of each subtask. The difficulty was scored from 1 to 5; score 1 indicates very easy and 5 represents very difficult. If the subtask failed, the investigator had to perform the same subtask again until the subtask was completed. The number of trials of each subtask was recorded and the causes of the failed trials were documented. The motion plans that the investigator used were also documented.

RESULTS

The investigator was capable of completing the six tasks on the ADL task board with above average performance. The task board performance showed that the investigator was well trained in using the JACO ARM (big button: 2.4 sec, elevator button: 3.1 sec, light switch: 2.6 sec, toggle switch: 3.7 sec, door handle: 7.1 sec, knob: 7.2 sec, TP: 1.2 bit/sec) in comparison to able-bodied results (big button: 4.1±1.7 sec, elevator button: 10.1±6.7 sec, light switch: 8.5±5.4 sec, toggle switch: 9.1±4.0 sec, door handle: 20.7±25.7 sec, knob: 32.0±18.5 sec, TP: 0.362±0.153 bit/sec)

Sequential Tasks

The investigator was capable of completing the two sequential tasks using the ARM. However, not all subtasks were accomplished at the first trial. Table 2 and 3 demonstrate the difficulty score, number of trials, and the causes of failure when performing the two sequential tasks. The very hard (score 4 and 5) subtasks are colored red and moderate hard (score 3) subtasks are colored yellow.

The hardest parts of the Brushing Teeth were using the faucet (Figure 2). The reason was the faucet's location is hard to reach when the ARM shoulder joint is lower than the countertop height. Most other failures were caused by a slip or alignment and orientation problems. The glossy and shapeable toothpaste tube was difficult to hold in position with the ARM. The successful motion planning was to hold the toothpaste with fingertips instead of holding in the palm. The small objects such as toothpaste cap or toothbrush were also difficult to manipulate because the fingertips had to align precisely to hold the object firmly. Some unstable grasping poses resulted in orientation changes during movement. The toothpaste cap was too small for the ARM to manipulate. Therefore, investigator had to use their mouth to open.

Table 2. Tooth Brushing difficulty rating (1-easy, 5-hard), number of trials, and causes of failure trials.

Brushing Teeth	Difficulty	Number of Trials	Failure Cause
Pick up the toothbrush	1	1	-
Place the toothbrush with brush facing upward	3	1	-
Pick up the toothpaste	2	2	Slippery surface
Open the toothpaste cap	3	3	Sliding out
Put toothpaste on the brush	2	3	Occlude by the cap, alignment error
Close the toothpaste cap	3	1	-
Place the toothpaste	1	1	-
Pick up the cup	2	3	Slip off, wrong orientation
Turn on the faucet	4	5	Hard to reach, slippery handle
Fill water in the cup	2	3	Wrong orientation
Place the cup	1	1	-
Turn off the faucet	4	4	Hard to reach, finger slip off
Pick up the toothbrush	2	2	Wrong handling
Dip water on the toothbrush	3	3	Hard to align
Put the brush in the mouth	2	2	Wrong orientation
Brush teeth	2	1	-
Place the brush	1	1	-
Pick up the cup	1	1	-
Water the mouth	1	1	-
Place the cup	1	1	-
Pick up the brush	2	1	-
Wash the brush	2	1	-
Place the brush in the cup	3	2	Hard to align
Pick up the toothpaste	2	2	Slippery surface
Place the toothpaste in the cup	3	3	Occluded by toothbrush, knock over cup

Table 3. Results of preparing and then having a simple meal difficulty rating (1-easy, 5-hard), number of trials, and causes of failure trials.

Meal Preparation	Difficulty	Number of Trials	Failure Cause
Open the microwave door	5	5	Broken finger, stiff button, over weight limit
Open the refrigerator door	4	5	Jam fingers, slip off, wrong orientation
Take out the container	2	1	-
Close the refrigerator	1	1	-
Place the container in the microwave	3	2	Bump the circular plate
Close the microwave door	5	6	Stiff spring, bent fingers, hard to push back
Set timer to 1 minute	2	2	Overshoot
Start the microwave	2	1	-
Open the microwave door	5	5	Stiff button
Take out the container	1	1	-
Place the container on the table	1	1	-
Close the microwave	5	5	Stiff door spring, hard to push back
Open the container cap	2	1	-
Place the cap in the sink	1	1	-
Pick up the spoon	3	2	Slippery handle
Scoop food	3	3	Wrong orientation
Move to mouth	2	1	-
Place the spoon in the sink	1	1	-
Pick up the container	2	1	-
Place the container in the sink	1	1	-

In the preparing and then having a simple meal task, the most difficult tasks were opening the microwave and refrigerator doors. Because the microwave door can only be opened by pushing a button and the resistance in the door locking mechanical spring is strong, the fingers of the ARM would bend and broke and resulted in the overweight status error (red flashing lights). The first motion plan used for opening the refrigerator door was to put the fingers behind the door handle with a firm grasping pose to pull open the door. However, after the door was opened and swung to an angle, the fingers were jammed by the door handle and could not move any further (Figure 3-2). The successful motion plan for opening the refrigerator door was to hold the door handle with fingers on either side, which used an open grasping pose. But this provided the room for fully opening the door and prevented jamming the fingers. Another moderately difficult subtask was putting the container in microwave machine. The bottom of the container collided with the rotatable glass plate in the microwave if held by the handle. The successful approach was to hold the container at an angle instead using the handle.

DISCUSSION

The feasibility and efficacy of the ARMs in the ADL assistance is a challenging question due to the variability of ADLs and environments. The ARM performance relies on both familiarity with the control interface and motion strategies. The lower task completion time and higher TP performance on the ADL task board testing suggested that the investigator was efficient in using the 3-axis joystick. Thus, the effect from the unfamiliarity with control interfaces was minimized.

ARM Limitations

Although the ARM has similar physical features to human arms, such as fingers, range of motion, or grasping force, there are many dynamic limitations like agility, fingertip resistance, finger stiffness, dexterity, payload, or simultaneously translational and rotational motion. Because of occlusion the ARM's physical working space was unclear, it was difficult to plan until the ARM reached its pose limit. When reaching for the faucet hand, due to the reduced working space caused by the interference with the countertop edge, the ARM could not be fully extended and the investigator had to re-adjust the wheelchair for better reachability. In addition to these kinematic and dynamic limitations, lack of kinesthetic perception affected the amount of motion applied to the objects. While opening and closing the microwave door, due to the lack of awareness of how much force and torque was applied to the fingers and door button, it was difficult to correct motion planning before the fingers broke or the ARM overloaded.

Environmental Challenges

Environmental challenges, including size, surface conditions, fixation, and weight distribution of objects were other factors that affected ARM performance in sequential ADLs. If the size is too small like the toothpaste cap and the food container cover, the ARM could not manipulate the objects. The container adaptor alleviated the size limitations. The smooth surface like the toothpaste tube and spoon made it difficult to hold in place and cause a slip during manipulation.

Motion Planning

Results from Table 2 and 3 show that the investigator was able to complete both tasks, but there were many unsuccessful trials due to inadequate motion planning. This indicates that the first attempt was not often a robust motion plan. Due to the ARM limitations, the ARM was unable to act in the way humans perform. Although the ARM mimics human arm physical features, motion planning that works for humans may not work for the ARM. Thus, helping ARM users learn and develop viable motion plans for real live ADLs is an important part of training.

Additionally, alignment accuracy is challenging when occlusion occurred. There were several alignment errors in the testing, such as inserting the toothbrush and toothpaste back into the cup.

Figure 2. Brushing teeth task (left: pick up the toothbrush, center: turn on faucet with cup, right: fill cup with water).

Figure 3. Preparing and then having a simple meal sequence (1: push microwave door open button, 2: open refrigerator door with jammed fingers in the upper right picture, 3: take out the container, 4: set timer to 1 minute using knob, 5: push start button, 6: open container cover, 7: scoop food, 8: bring food to mouth).

CONCLUSION

This work demonstrated the feasibility of the ARM in completing self-care ADLs. Two self-care tasks, selected from the ICF, were successfully completed by a well-trained investigator. By analyzing the failed trials and errors during the testing, the ARM's kinematic and dynamic limitations and the kinesthetic perceptions made it difficult to re-adjust motion plan before errors occurred. In addition, environmental challenges were identified and we provided one example to alleviate the limitations. Due to the differences between the ARM and human motions, some intuitive human motion plans were not applicable to the ARM motion. Therefore, developing robust motion planning for the ARMs is another important factor to secure successful ADL task completion.

Future work will include exploring more self-care ADLs with a larger sample size of ARM users and people with upper extremity impairments in conjunction with development of ARM accessories to ease the barriers. The ultimate goal is to provide feasible motion planning and an ARM-friendly environment so that the ARM users can live independently

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