FINAL REPORT
PROJECT GRANTS
CREATING OPPORTUNITY & INDEPENDENCE
Craig H. Neilsen Foundation

Five-page maximum (retain all questions)

Organization Name	Tufts University		
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Project Title	**Robotic Assistance for Activities of Daily Living for Persons with C4-C7 Spinal Cord Injury**		
proposalCENTRAL ID#	519406	**Date of this Report**	11.25.19
Award Amount	$74,121		
Grant Term (MM/DD/YY–MM/DD/YY)	Oct. 31, 2017 – Oct. 30, 2019		

1. SUMMARY
Summarize the goals of this project as originally proposed and the status of the project at completion. Include any opportunities and/or barriers that affected achievement of the goals for this project.

The purpose of this project was to develop and assess the feasibility and usability of robotic assistance for individuals with C4-C7 SCI to perform targeted activities of daily living (ADLs). A collaborative iterative approach was used that included an interdisciplinary team of engineering and occupational therapy faculty researchers and students from Tufts University and Rensselaer Polytechnic Institute (RPI) and community partners (CPs) and their care support people. CPs were five males aged 28-60 living with C4/5-C6 SCI from the Greater Boston area. Initially, we focused on using and modifying the Baxter on Wheels (BOW; a large robot available at both lab locations) to develop protocols, user interfaces (UI), accessories and environmental modifications. Formative and summative feedback gained from this phase informed the design and development of two smaller, more mobile robot platforms: Cartbot and OARbot. CPs preferred functionality over aesthetics and wanted the option to operate the robot using both manual (joystick) and automated (voice-activated) control (*supervised autonomy*). Videos of lab sessions with all robotic systems can be found here.

2. BUDGET
Summarize expenditures for this grant on the CO&I Grant Expenditure Report template (located at the bottom of the Deliverables page). The completed expenditure report must be uploaded as a separate PDF file.

3. PARTICIPANTS
a. *Total number of participants in this project/program:* ___8_______

b. *Number of individuals with SCI served by this project/program:* ____5______

c. *Original proposed number of participants with SCI to be served by the project/program:* ___6_______

d. *Explain any discrepancy between b. and c. above.*
We worked with 5 people with C4/5-C6 SCI and 3 of their support people all of whom provided feedback in the development of the robotic assistive devices and accessories. We had recruited a 6th individual with SCI, but health issues prevented him from being able to travel to the robotics lab to participate in the project.

4. OUTCOMES

a. *List the outcomes as proposed and describe progress toward completion of the project goals. Include objective measures when possible. (e.g., three manuals completed and printed, metric for enhanced care of individuals with SCI, website complete and online at____).*

1. **Identify general and task/situation-specific verbal commands/prompts to perform selected activities of daily living (ADLs).**

1a. Voice commands linked to automated robot movements were developed in May 2018 and updated throughout the study to direct the robot in performing targeted activities of getting a water bottle out of a refrigerator and removing a plate of food from a refrigerator and heating it up in a microwave.
1b. A laptop-based vocal command user interface (UI) that incorporate voice commands (using Amazon's "Alexa" voice interface) was developed to give CPs a list of voice commands associated with specific activities and to provide CPs with feedback regarding where the robot was in relation to performing a selected task and the state of the environment as perceived by the robot. The UI enabled CPs to know which voice commands to give the robot at particular points in time to perform targeted tasks.
1c. The UI allowed CPs to command the robot to open the fridge and microwave doors, and then use a combination of voice commands and joystick control to retrieve objects from inside the fridge or microwave and return to CPs.

2. **Develop training/procedural guidelines (and the user interface) to operate the robot.**

2a. Flow charts that connected voice commands associated with automated robot actions were initially created followed by a laptop-based UI (described above) so CPs could use voice commands to operate the robot to successfully to perform the targeted activities. As CPs became more familiar with guiding the robot, they preferred using the laptop-based user interface over the flow charts.
2b. The laptop-based UI displayed only the viable commands at each stage of the robot's action to ensure that commands were given in correct order, e.g., giving the command to open the fridge before giving the command to select a bottle from the fridge.

3. **Assess the effectiveness of training/procedural guidelines and accessories** Over the course of this research, we conducted a total of 13 two-hour lab sessions and six 60-minute phone-based interviews with 5 CPs to develop and assess the robotics systems. Three care support people provided input at the onset of the study and asked that subsequent feedback to come solely from CPs given their expertise and lived experience. From November 2017 - November 2018, both the Tufts and RPI labs developed and worked with the "Baxter On Wheels" (BOW), a large dual-armed robot fastened to a power wheelchair base that is driven by joystick control. Baxter's arm and gripper movements were operated by voice command. Five CPs participated in lab sessions with the robot to provided formative and summative feedback regarding usability and modifications needed to improve performance.

3a. Two on-site lab sessions were held with each CP between May and September 2017 in which they used the robot to: 1. get a water bottle out of a refrigerator; 2. remove a plate of food from a refrigerator and heat it up in a microwave. Post-session interviews with CPs showed they had a strong preference for having assistance retrieving objects from the floor, so this activity was added to the list during the first year of the study.
3b. Accessory attachments were developed for the robot's grippers so it could handle and move containers of varying size, shape and weight.
3c. CPs reported a strong preference for customization and freedom of use, so the team developed methods of both manual (joystick) and automated (voice-activated) robot control.
3d. All CPs agreed that BOW was too large for their natural living environment, with preference for a smaller, more navigable unit. CPs unanimously preferred functionality over aesthetics, and rated precision, reliability, size and cost to be very important for robot-supported assistance. All CPs identified that a robotics system would be useful as assistive technology by providing welcomed independence in performing the selected activities for this project in addition to suggesting additional uses such as retrieving books from a shelf and dispensing medications.

The BOW demonstrated the feasibility of robotic assistance for ADLs, but it is too large, heavy and cumbersome for practical use. We received a one-year no-cost extension to address these shortcomings to develop and test two separate more mobile robot platforms: “Cartbot” was developed in the Tufts lab while “OARbot” was developed at the RPI lab.

Cartbot

Cartbot is a low-cost assistive mobile manipulator with simplified kinematics. Cartbot consists of a cylindrical robotic manipulator, a two-wheel drive system with independently controlled motors, and a shopping cart-based chassis (see "Cartbot" videos). The purpose of this design is to give the user complete manual control over the system through direct joystick manipulation (to drive the cart and manipulator), giving them full agency over its operation in an intuitive, easy to understand way. Providing complete manual joystick control also allows a level of full control that enables the user to utilize their own cognitive and vision capabilities to perform complex tasks in unstructured environments and unpredictable situations.

Cartbot was ready for testing starting in April 2019. Three CPs engaged in on-site lab sessions to perform two separate bottle retrieval tasks. The first task required them to move a bottle from one platform to another platform at a different height. The second task required them to move a water bottle from inside a refrigerator to a nearby platform. A different bottle was initially placed in front of the target water bottle inside the refrigerator, obstructing the robot’s path to reach it, and the users were not instructed on how to address the obstacle to determine how they would navigate this challenge. CPs successfully performed these tasks and pointed out that the type of bottle the team was using was impractical because they used larger, heavier water bottles in their daily lives. The team spent the next few months developing grippers and a stronger robotic arm that could handle larger, heavier objects.

In October 2019, two more lab sessions were conducted with three CPs who were tasked with retrieving an item from each appliance (bottle from refrigerator, food container from microwave) and moving them to a nearby platform using the Cartbot system. Two different grippers were equipped on the Cartbot to match the form of each item. CPs could successfully perform these tasks but were challenged with being able to know where the robot gripper was in relation to the object it was retrieving, so the team added a camera to the arm near the gripper, which improved performance.

All three participants agreed that the freedom that joystick control of the system had was desirable given the agency it provided them in executing tasks. The participants with C5 SCI and C6 SCI reported that the system was easy to use, while the participant with C4/5 found it slightly difficult to use. This participant stated that controlling gross movements of the joystick was straightforward but controlling fine movements with the joystick was difficult. This CP suggested that alternative manual input devices such as a sip-and-puff joystick (e.g., Quadstick) could make it easier to use.

“OARbot”:

The RPI lab developed a smaller footprint device with a Kinova (by Jaco) robot arm mounted on a vertical lift and an omni-directional mobile base (see “OARbot” videos). The arm has a three-finger hand and is equipped with a wrist 3D camera to provide closeup views. This device was named Omnidirectional-Assistive Robot (OARbot). Based on CPs’ feedback, OARbot operation is based on *supervised autonomy*, meaning that users have the option of using both manual (joystick) and automated (voice-activated) control of the robot. To help OARbot navigate in a room, we have instrumented two Kinect sensors on the ceiling to provide a complete map of the room, including objects (e.g., appliance) and people. To retrieve an object from the fridge, the user presses a button on the laptop screen, and the OARbot automatically navigates to the fridge using the map of the room. With the fridge door opened using the automated door opener described below (in Accessories), OARbot will scan the interior of the fridge, prompt the user to point to the object of interest, and bring the object back to the user. OARbot can also be manually operated using quadstick input. This system was developed in the RPI lab and was positively supported by CPs when they were shown videos of OARbot in operation, but it has not been directly tested with CPs.

Accessories:

An automated door opener for kitchen appliances (refrigerator and microwave) was developed to add to the functionality of the system without increasing the complexity of the mobile manipulator robot. The device opens and closes their respective door based on voice commands given by the user. The voice commands were “open the fridge/microwave” to open, and “close the fridge/microwave” to close. All CPs agreed that the automatic door opener was helpful and easy to use. Additionally, a universal joystick interface that accepts any size, shape and style of joystick "toggle" was developed for Cartbot so that all CPs could successfully use it.

Dissemination

Project findings will be disseminated in two peer-refereed scientific poster sessions at the American Occupational Therapy Association Annual Conference in Boston, MA (March 2020) and a paper was submitted to the ACM/IEEE International Conference on Human-Robot Interaction conference in Cambridge, England (March 2020). Our ongoing work has been demonstrated and presented internally to interdisciplinary faculty and students. Additional journal and conference papers/posters are being or will be prepared to disseminate our ongoing research and development.

b. Explain any outcomes not completed and their effect on the impact of this project.

All outcomes were completed for this project.

5. PROGRAM EVALUATION

a. Report on project/program evaluation, including both objective results (e.g., data collected, equipment obtained, number of participants, changes in number of patient visits) and subjective results (e.g., results of patient surveys, staff focus groups, expanded programmatic efforts, observations on processes utilized).

Summary of Project/Program Evaluation:

The collaborative person-centered iterative design process yielded a voice-activated robot placed on a power wheelchair base (BOW) that was maneuvered via joystick control. The team developed a control box with a universal joystick that accepted any knob attachment so all CPs could maneuver the robot with efficiency. Voice commands associated with automated robot actions was created along with a laptop-based user interface so CPs could use voice commands to operate the robot to successfully perform the targeted tasks. Accessory attachments were developed for the robot's grippers to enable it to successfully handle and move containers of varying size, shape and weight. CPs showed a strong preference for customization and freedom of use, i.e., they identified that it would be most useful and important for the robotics system to include *supervised autonomy*, meaning that they have control of the robot and have the re is an option of having both manual (joystick) and automated (voice-activated) control of the robot. All CPs agreed that BOW was too large for their natural living environment, with preference for a smaller, more navigable unit. Thus, we developed initial prototypes of Cartbot and OARbot. CPs significantly preferred functionality over aesthetics, and rated precision, reliability, size and cost to be very important for robot-supported assistance. All CPs felt a robotics system would be useful as assistive technology by providing welcomed independence in performing specific household ADLs.

Objective & Subjective Results:

The design of the Cartbot system was informed by our investigation with the BOW system in that it aims to reduce the system footprint, significantly lower the cost, and allow the user complete manual control over operation, while allowing for high-level control through voice activated autonomous movements. The Cartbot design is also intended to allow for modular attachments for customizability to user preferences. The wire-frame chassis design affords simple attachment through various clamp interfaces. The OARbot design aims to reduce the system footprint, use less space and be able to move sideways for easy navigation and adjust height for broader reach. It is operated by voice and joystick modes. OARbot is designed to work within a "smart room" where two ceiling mounted Kinect sensors track people and objects inside the room. The user would be able to command OARbot to autonomously navigate to the appliance, perform tasks, and retrieve objects back to the user – with the appliance and user locations identified by the ceiling sensors.

Project findings provided support for continued development of robotic assistive technology to help persons with C4-C7 SCI perform ADLs. Findings informed future directions that provide customizable options related to automated and manual robotic operation, precision in movement, reliability, size and cost.

6. IMPACT

a. Describe the most significant accomplishments resulting from this grant

The four most significant accomplishments resulting from this grant were the following:

1. Demonstrating getting a drink, making a microwave meal, and picking up an object from the floor using robotic systems that include supervised autonomy;
2. Involving our community partners as experts for developing and improving the systems which had a major positive impact on the learning and collaborative solution-based decision-making of our interdisciplinary team and particularly our undergraduate and graduate students;
3. Developing smaller mobile platforms for the robotic manipulators (Cartbot and OARbot);
4. Conceiving and implementing prototypes of an *Integrated Modular Assistive Technology (IMAT)* system.

The fourth accomplishment warrants some discussion. Work with the BOW indicated that its size and complexity would be impractical for use because of the difficulty of maneuvering and controlling them. For these reasons, both the RPI and the Tufts teams moved to smaller mobile platforms. Just as significant, expense must be considered. The IMAT approach addresses cost and other challenges. The IMAT system consists of stationary and mobile modules, both passive and motorized, that are specialized for one or a few tasks. The specialization (e.g. opening and closing a microwave or picking up an object off the floor) allows the mechanisms to be simple, reliable, easily replaceable, and most of all *inexpensive*. An apt analogy is kitchen gadgets for specific tasks like opening a can or mixing. Offloading many of these tasks allows for a lighter, simpler, and less expensive robot. The motorized modules are commanded by voice control or sip-and-puff interfaces, allowing CPs to accomplish complex task much more quickly and reliably, because accomplishing certain subtasks (like opening and closing a microwave and a refrigerator for making a microwave meal) can be done in parallel with moving the manipulator into position, and do not require the fine control of the robot.

b. What impact has this project had on the organization and quality of life for individuals with SCI served by the organization?

All five CPs reported that involvement in this project was empowering for them. Also, they all support continuing development of robotic assistance for ADLs because, as reported in exit interviews, it gives them increased agency and autonomy and improves quality of life.

c. What was the most unexpected benefit and/or challenge experienced during the grant period?

The most unexpected benefit during the grant period was collaboration with an integrated interdisciplinary team of faculty, students in addition to including Community Partners as <u>experts</u>.

7. SUSTAINABILITY

Describe plans put in place by the organization (or partner organizations) to sustain and build on the progress made during this grant.

During this project, both labs moved towards the development of smaller and more mobile assistive robots. Feedback from initial user testing is unanimously positive and supports our design approach. We intend to continue with this important research through interdisciplinary and cross-school teamwork. All of our future work in this area **<u>must</u>** include CPs as co-investigators. We will focus our work on further development and testing of Cartbot, OARbot and the Integrated Modular Assistive Technology (IMAT) systems approach. We will continue to emphasize and assess functionality, precision, reliability, size and cost. We will continue to seek out funding to support this important work through existing lab resources and internal and external grants, such as Tufts Clinical and Translational Science Institute (CTSI); Craig H. Neilsen Foundation's, Spinal Cord Injury Research on the Translational Spectrum grants; and the National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR).

8. PROJECT PRODUCTS

Forward copies of all project products created as part of this project (e.g., manuals, resource guides, promotional materials, etc.) to:

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