3D Joystick for Robotic Arm Control by Individuals with High Level Spinal Cord Injuries

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***Abstract*— An innovative 3D joystick was developed to enable quadriplegics due to spinal cord injuries (SCIs) to more independently and efficiently operate a robotic arm as an assistive device. The 3D joystick was compared to two different manual input modalities, a keyboard control and a traditional joystick, in performing experimental robotic arm tasks by both subjects without disabilities and those with upper extremity mobility impairments. Fitts's Law targeting and practical pouring tests were conducted to compare the performance and accuracy of the proposed 3D joystick. The Fitts's law measurements showed that the 3D joystick had the best index of performance (IP), though it required an equivalent number of operations and errors as the standard robotic arm joystick. The pouring task demonstrated that the 3D joystick took significantly less task completion time and was more accurate than keyboard control. The 3D joystick also showed a decreased learning curve to the other modalities.**

Keywords*— Assistive technology; multimodal HCI; robotic arm; spinal cord injury; quadriplegia; 3D joystick.

I. INTRODUCTION

Recent advancement in computers and robotics makes it possible for people with spinal cord injuries (SCIs) and other upper limb mobility impairments to perform daily living and other tasks more independently through the assistance of a robotic arm [1]. However, operation of robotic arms has always been challenging, particularly for individuals with upper limb extremity mobility impairments. Two great challenges are faced by persons with SCI to efficiently control robotic arms. One is that the traditional manual user controllers for robotic arms require fine motor skills, which is extremely difficult for this group of users, or very technically complex, such as eye-tracking, speech control, and brain-computer interfaces (BCI) [2, 10, 11, 12]. The other challenge is that each potential user has their own motor skill abilities and preferences even when comparing individuals with the same level of SCI. Therefore, the type of user interface is very individualized and may require significant customization to accommodate each subject [3].

Some kind of human-computer interface (HCI) must be employed to initiate and orchestrate the task. Multiple methods have been suggested to manipulate a robotic arm with sufficient dexterity to accomplish most basic tasks, such as picking up items, drinking from a glass or self-feeding. However, there are very few HCI methods that are designed specifically to facilitate individuals with upper extremity mobility impairments [4, 10, 11, 12].

In this paper, three different robotic arm control systems that provide different methods of user input selection were evaluated to assist quadriplegics due to SCI. The system could not only be used to assist people with quadriplegia for activities of daily living, such as eating, drinking and dressing, but also allow students/scientists with quadriplegia the ability to perform laboratory procedures and other "hands-on" activities more independently providing unprecedented opportunities to actively participate in education and different types of careers.

II. RELATED WORK

User control modalities to assist people with disabilities to operate a robotic arm have been previously studied. A physical joystick is a widely accepted modality for the control of robotic arms. Joysticks are standard components for most commercially-available robotic arms, which allow the user to operate the end effector through directed selection [5]. The physical joystick is inexpensive, simple in design and can provide accurate control. However, many robotic arm joysticks [6] provide two-dimensional control for x and y directional control and to control z direction by using a twisting control knob or separate controller. This is sufficient for able-bodied individuals, but has limited use for people with limited or no finger or hand mobility, such as those with upper level SCIs [7]. Another very popular interface for robotic control is automatic speech recognition system. It is considered as a solution to the problem of traditional joystick. For example, a

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system called FRIEND, operates a robotic arm attached to an electric wheelchair using a speech interface with simple commands [8]. Unfortunately, speech control is limited to discrete commands and not robust in noisy environments. This makes user control extremely difficult outside or where there is significant background noise. There is also significant safety issues present with speech recognition systems due to unintentional activation. Other interfaces that have been proposed to operate a robotic arm system to assist individuals with disabilities include gesture-based interface [9], BCI [10], and eye gazing control [11] are in their infancy and still have significant technical challenges to overcome.

III. Methodology

The multimodal robotic arm user control systems consisted of three parts: a PC workstation, the different controller types (default joystick, keyboard or 3D joystick), and the actuated robotic arm (JACO^{TM} Robot Manipulator from Kinova Technology as shown in Figure 1). The default controller for the JACO arm is a traditional joystick to control the movement of certain elements (i.e. arm, wrist) in two dimensions (see top of Figure 2). Movement of the robotic arm in the 3rd dimension requires rotation of the joystick knob. This motion is extremely difficult or even impossible for individuals to perform with complete high-level (Cervical levels 1-8) SCIs.

Fig. 1. JACO robotic arm ready to grasp a water bottle. It can also be mounted to a wheelchair.

Two alternative modalities were developed in this project to serve as superior user controllers for this robotic arm for quadriplegic users. The first alternative input method developed was through keyboard control (top of Figure 2). Keyboards are widely used as a direct selection device for efficient and naturally intuitive operation. For keyboard operation, all the functions for robotic control were mapped to specific keystrokes (i.e up, down, left, right, forward, backward, change mode). Three keyboard input control modes were programmed: discrete, continuous and hybrid (a combination of discrete and continuous) modes. During discrete mode, the robotic arm moved in small increments every time a key was pressed. During continuous mode, the arm would move continuously until stopped or another key to change directions was pressed. During hybrid mode, subjects could toggle between discrete and continuous modes at their discretion.

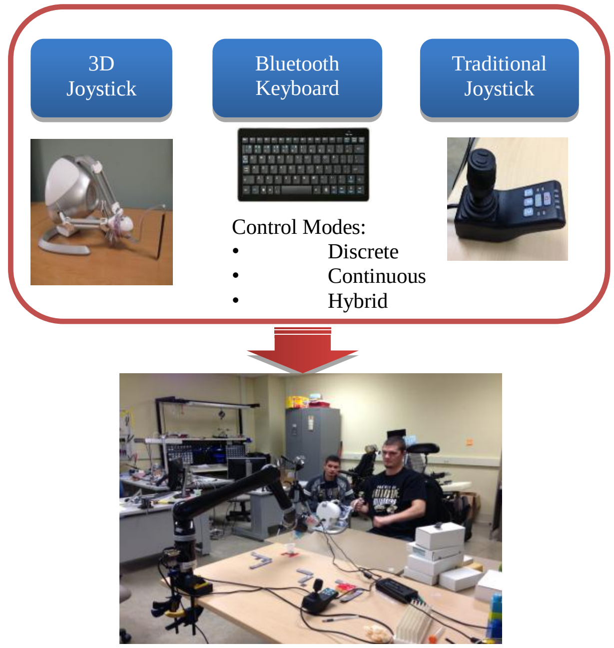

Fig. 2. Subject with a SCI using the 3D joystick to perform the pouring task.

The other alternative control modality was a 3D joystick (Figure 3) which was originally designed for haptic video game playing by Falcon Technology®. It was reprogrammed and adapted as a 3D joystick controller for the robotic arm. A handle developed for users with no finger gripping ability was positioned in the center of the joystick. The 3D joystick provides users a method of directed selection to control the robotic arm elements to move in 3D Euclidean space. The handle of 3D joystick was positioned at the center of the joystick as a home (or rest) position if not used by the user.

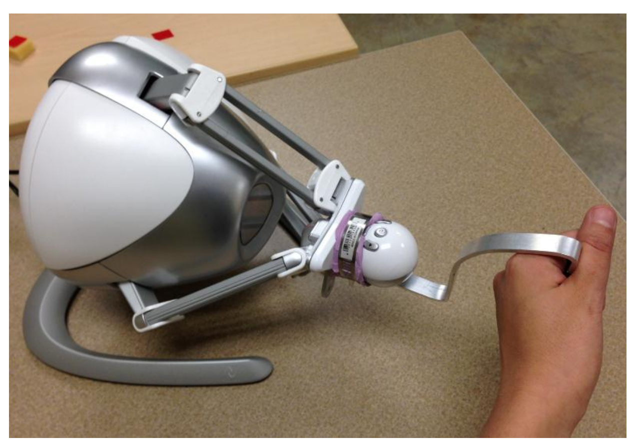

Fig. 3. 3D joystick with adapted handle for quadriplegic users.

A force feedback control with a proportional and differential (PD) controller force the handle back to the center after each manipulation. The control diagram for 3D haptic joystick is shown in Figure 4. A JACO API was used to functionalize the haptic joystick to achieve 3D control of the robotic arm.

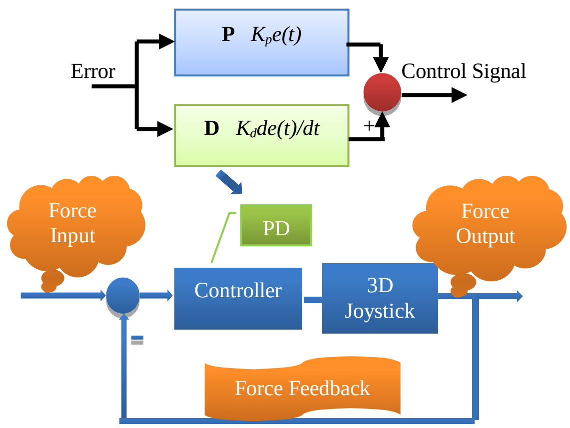

Fig. 4. 3D joystick control diagram.

IV. EXPERIMENTS AND RESULTS

Two sets of experiments (Fitts's targeting and pouring tasks) were conducted to evaluate manipulation performance through robotic arm control instead of computer simulation of 3D graphical model (used widely for input modality testing). The robotic arm manipulation was selected because it was task centered and can provide more thorough subject assessment of input modality usability and performance. Further, robotic arm control allows subjects to easily view arm movement in three dimensions. The focus of this study was to enable individuals with SCIs at the most common mid-cervical neurologic levels, which lead to gross motor function of the shoulders and elbow flexion, to effectively operate a device in 3D. Two subjects with Cervical-4/5 and Cervical-6 SCIs and three subjects without disabilities (ages 25-42) were recruited for these experiments. For the two subjects with SCIs, one had limited wrist function while the other did not and used wrist braces for fixating the wrist. Neither subject had hand or finger movement. During the experiments, each device was positioned according to subject preferences for robotic control. During the Fitts's targeting task, the relative accuracies of each of the input control modalities were compared by the subjects' abilities to touch the tip of a pen held by the robotic arm (Figure 4, left side) to different sized and positioned targets as quickly as possible. The two targets, sizes 2.8 x 2.8 cm and 8.0 x 8.0 cm, were alternately placed at locations 40cm and 70cm from the base of the robotic arm. Fitts's Law result for this targeting task performed five each is shown in Figure 5. The slopes for the 3D joystick, traditional joystick, discrete (keyboard), continuous (keyboard) and hybrid (keyboard) control modalities were 2.7, 3.08, 3.79, 4.73, and 3.58 respectively. The 3D joystick had the smallest slope or the highest index of performance (IP) (reciprocal of the slope). A higher IP for the 3D joystick indicated a greater human rate of information processing during the targeting task.

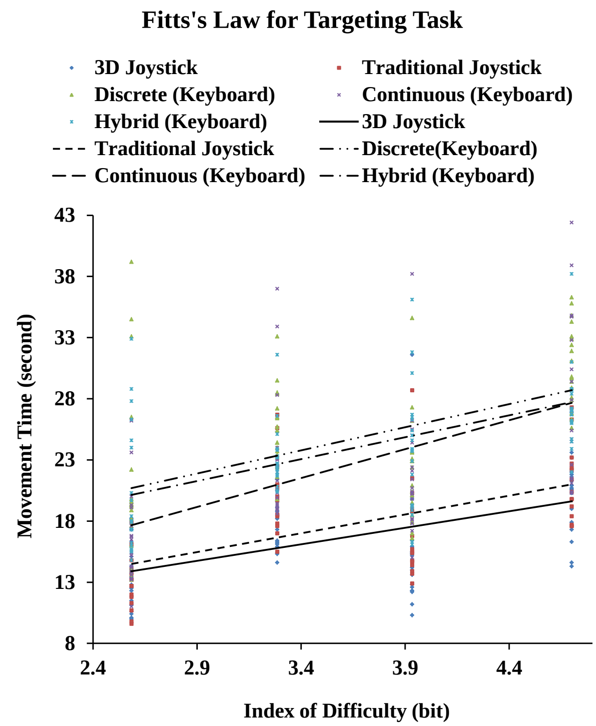

Fig. 5. Fitts's Law for each input control modality.

Figure 6 shows the average number of required operations and errors (changes in direction by the user due to incorrect movements) for performing the targeting task for each input control modality. The input modalities that require a greater number of operations and cause more errors are likely to lead to more user fatigue during operation. The keyboard under discrete control mode required the least number of operations. The keyboard under continuous mode resulted in a significantly greater number of operations and number of errors than the 3D joystick, which was equivalent to the traditional joystick.

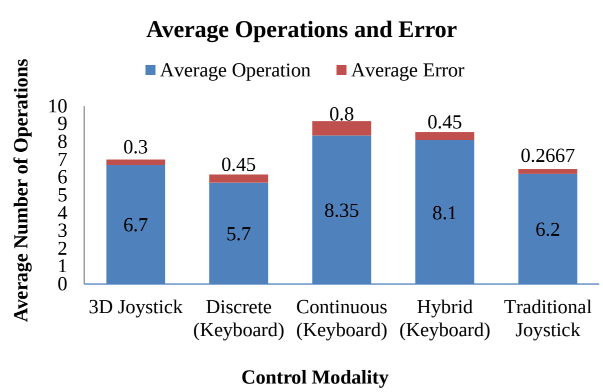

Fig. 6. Average required operations and error for each control modality for the targeting task.

The second experiment was a pouring task performed by each subject five times. The robotic arm had to be navigated to a specific location, grab a bottle with 100 solid particles, pour these particles into a beaker with a 4.5cm diameter opening, and then replace the bottle to its original position. Figure 7 showed the average task completion time (with standard deviation error bar) and accuracy (number of spilled particles) for the 3D joystick, keyboard in hybrid mode, and traditional joystick. ANOVA test showed no significant difference between 3D joystick and traditional joystick in task completion time, while keyboard control was significantly slower than the 3D joystick during the pouring task. The 3D joystick also had a greater average accuracy than the other controllers.

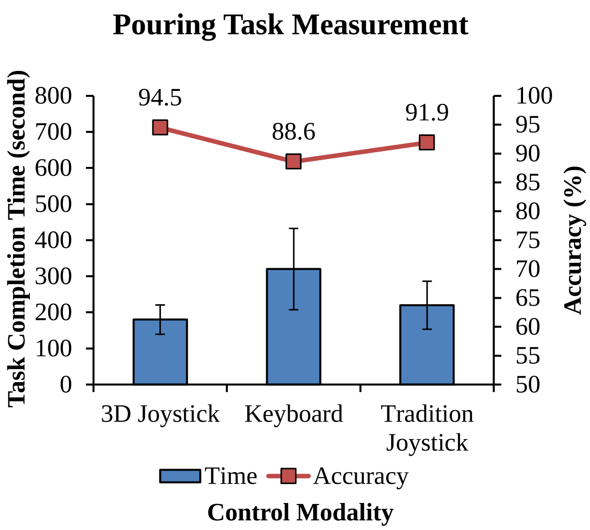

Fig. 7.Average task completion time and accuracy for pouring task. Significance was at p<0.01.

In Figure 8 and 9, the learning curves for task completion time and accuracy of subject with SCIs and able-bodied subjects using the three input control modalities indicated a general trend in greater performance with subsequent tasks. The 3D joystick showed less performance differences between the first and last experimental task for 3D joystick, which indicates greater intuitiveness of use.

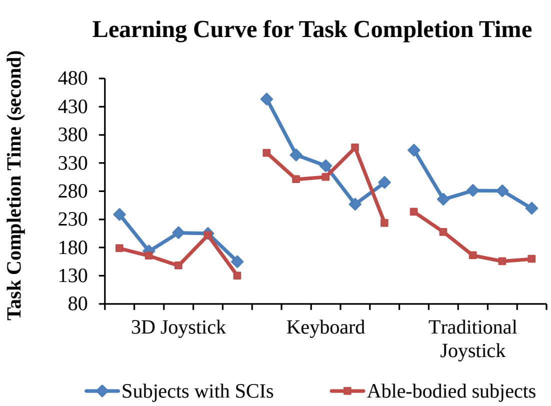

Fig. 8. Learning curve of task completion time for subjects with SCIs and able-bodied subjects for each control modality in the targeting task.

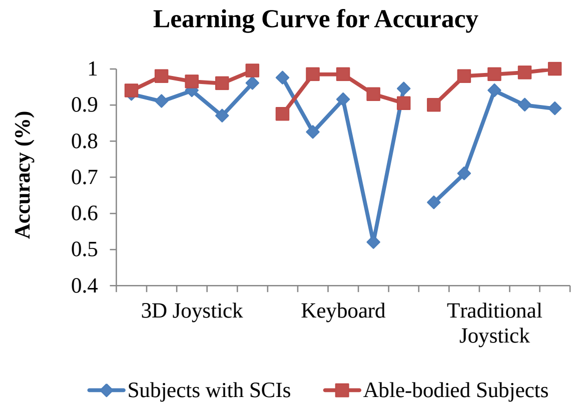

Fig. 9. Learning curve of accuracy for subjects with SCIs and able-bodied subjects for each control modality in the targeting task.

Conclusions and Future Work

This paper proposed an innovative 3D joystick, based on user-centered design for individuals with upper extremity mobility impairments, as a more efficient and intuitive controller for operating a commercial robotic arm. Ideal users for the proposed 3D joystick would be quadriplegics with some upper limb mobility. When performing a Fitts's law targeting experiment for the three different input control devices, the 3D joystick achieved a higher IP. During the pouring task the 3D joystick was as efficient as the traditional joystick that came with the robotic arm. However, one subject with SCI could not manipulate the traditional joystick at all due to an inability to twist the joystick knob. The other quadriplegic subject could twist the knob using a two-handed approach. For all the input modalities adopted in this paper, no method seemed to be overtly more physically demanding to users than the other. Keyboard usage was the slowest input modality; however its direct selection method arguably required the least demanding physical action. The need for alternate input controls for users with disabilities to more efficiently operate robotic arms was apparent in this study.

Future work will include recruiting quadriplegic subjects with primarily fine motor function, such as muscular dystrophy, multiple sclerosis or rheumatoid arthritis for 3D joystick evaluation and evaluating fatigue and investigating techniques to support or brace the arm during 3D joystick usage.

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