VIA: A Virtual Interface for the Arm of Upper-limb Amputees

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Abstract

Many upper-limb amputees retain the ability to control a hand, however no suitable mechanical hand is available to them. A hand/arm virtual interface (VIA) developed at Rutgers allows amputees to manipulate objects within a virtual environment. The interface uses residual myo-kinetic signals expressed at the surface of the forearm to control the virtual hand, while arm reaching is transduced by a goniometer. In preliminary tests amputees readily gained control of the virtual hand, and successfully used it to manipulate objects. This is indicative of *VIA usefulness as a tool for assessing and training amputees in using a dexterous mechanical hand.*

Keywords

Virtual reality, myo-kinetic interface, training, upper-limb amputees

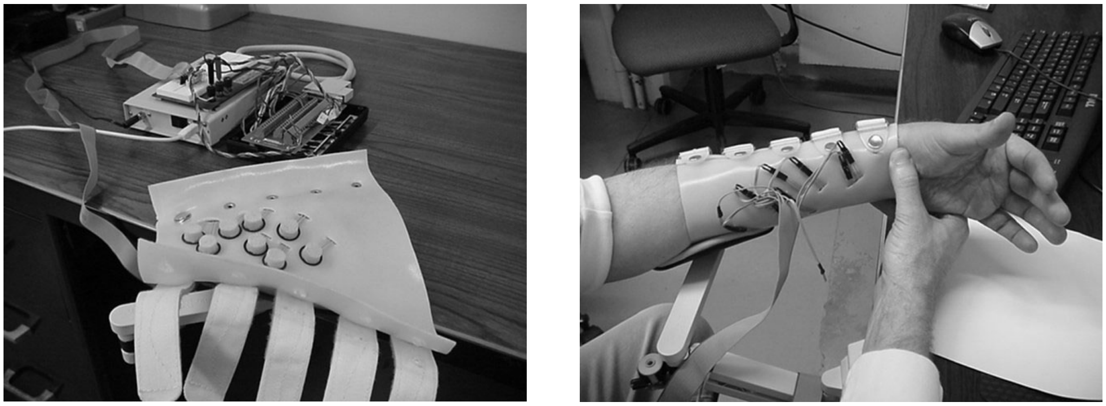
INTRODUCTION

Off-the-shelf Virtual reality equipment and application software are designed for individuals with intact limbs. In the case of patients with upper or lower extremity amputation their anatomy has been altered, yet virtual reality is benefiting them in several ways. One is in correcting the gait of lower extremity amputees, where VR equipment (head mounted displays) has been used to present to a patient a stereoscopic video of her walking [6]. Another way VR has been used to benefit amputees is in the design of prosthetic arms. Here VR becomes an integral part of the CAD design of the associated mechanisms, through what is now called “virtual prototyping.” Furthermore, visualization of the prosthetic arm in virtual reality [3] helps potential users better understand its functionality. Visualization in VR also helps amputees cope with the so-called “phantom pain” [4]. This interesting phenomenon is associated with pain an amputee feels in his lost limb. Virtual reality can help visualizing the lost limb by mirroring the intact one, and helping the amputee control this virtual image to a less painful pose.

The present paper represents initial work in yet another VR application for amputees. Here VR is used to help train the patient in the use of a myo-kinetic interface prior to fitting with a prosthetic arm. The myo-kinetic interface is the sensing element that reads the patient’s bio signals subsequently used to control the prosthetic arm actuators. Section 2 describes the experimental setup used in the present study. The graphical user interface and other software components are detailed in section 3. Sections 4 and 5 present data from an initial proof-of-concept testing of the prototype system, looking at objective training variables (task completion time and error rates). Conclusions and future work directions are the subject of section 6.

EXPERIMENTAL SETUP

The interface developed by our group utilizes force-sensing resistors (FSRs- Interlink Electronics, Camarillo CA). These sensors are fabricated from thick film conductive silicone composite that exhibits decreased resistance with increased applied force. The resistance response to force is a nonlinear power law function, ranging from 100 kΩ at 50 gram force to 1 kΩ at 1000 gram force and higher. This range is suitable for detecting superficial forelimb activity, which may be as much as 500 gram force. Highly elastic low-density silicone foam discs are attached to the FSRs to ensure an intimate fit with the forelimb and to provide a pre-load stress which will allow the sensors to detect negative changes in stress, essential for identifying unique pressure patterns. Eight FSRs are mounted on the inner surface of a sleeve, constructed of fabric-reinforced silicone. The sleeve forms a mechanical support necessary to place the sensors over sites on the palmar surface of the forelimb most likely to demonstrate mechanical activity (see figure 1a). The sleeve is worn over the forelimb and fastened by multiple straps that allow the user to tighten the fit, thereby pre-loading the sensors.



(a) **(b)**

Figure 1. Sensory sleeve: a) FSR sensor with silicone foam discs line the inner surface of a sleeve. A hardware interface acquires signals from the sensor array; b) A normal subject dons the sleeve and places the arm in the tracking armrest.

An armrest was modified to include two potentiometers at rotating joints that track the lateral motion of a forearm with the attached sleeve, as shown in figure 1b. Half-bridge voltage divider circuits assembled on a breadboard are used to convert FSR and potentiometer resistances to voltage levels that are acquired by a data acquisition board (DAQPad-6020E, National Instrument Corporation, Austin, TX) through a connector block.

A program developed on a PC with LabVIEW (National Instruments Corporation, Austin, TX), a graphical programming language, consists of a filtering algorithm similar to the one developed in [2] and a user interface. The program has two modes: training and operation. Weights for a pseudo-inverse filter [4] are determined during an initial training procedure, where a subject is instructed to perform multiple repetitions of three independent motions. The user interface guides the subject through the training procedure with visual and audio cues. As the training motions are completed, filter coefficients are computed and stored. During operation mode all pressure inputs are filtered to obtain output signals that are proportional representations of the intended motions in near real-time. Data representing volition intensity and armrest position are transferred from LabVIEW to the Java application using DataSocket. DataSocket [5] is an API provided by National Instruments for real-time sharing of data between different applications in the same computer or between clients in different platforms over the Internet.

VIRTUAL ENVIRONMENT

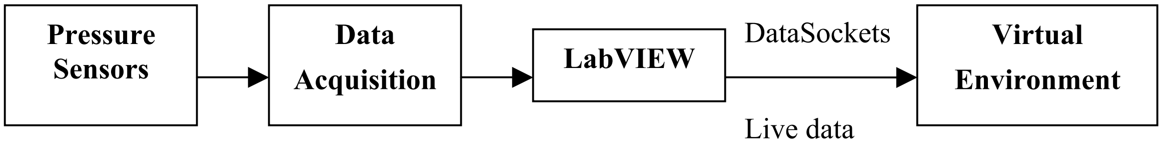
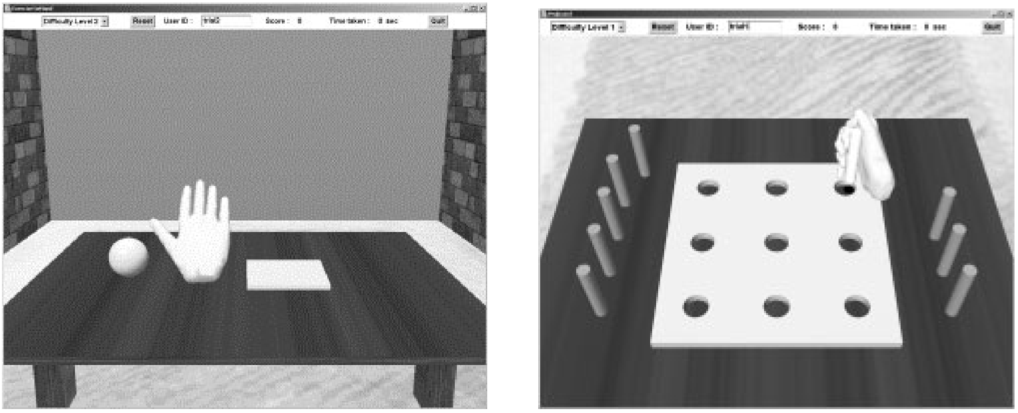


Figure 2. VR based rehabilitation system block diagram.

The virtual reality based training exercises use Java3D for rendering and updating the graphic scene. Based on a recent survey [1] of desired activities of trans-radial patients, two exercises (pick-and-place and pegboard filling) involving grasping were chosen for training. The pick-and-place exercise consists of a simple virtual environment with a ball and target placed on a table presented to the subject. The virtual environment also contains a model of a hand used to interact with the virtual environment. The virtual hand is animated based on the signals from the sensorized sleeve, transmitted through the use of DataSocket (see figure 2).

The task assigned is to pick the ball with the virtual hand and to place it in the target area. The target is a rectangle located on the table surface (see figure 3a). The positions of the ball and target are randomized in order to avoid quick adaptation of subjects to the virtual environment. The distance between the ball to be picked and the target is made constant to keep the measurements consistent. The time taken to pick up the ball and place it on the target is computed, displayed on screen and stored in a database.



(a) (b)

Figure 3. Virtual rehabilitation exercise. a) Pick-and-place exercise. b) Pegboard exercise.

The target rectangle changes size depending on the trial level of difficulty. The target is set to 3X, 2X, or 1X the ball diameter. Naturally, the smaller the target rectangle, the higher the difficulty level of the task. Appropriate scoring is assigned for each level of difficulty. If the ball is dropped outside the target area, an error is recorded. A simple scoring system is implemented to make this exercise into a game. Scores are displayed on the screen along with sound feedback to reward the patient for correct placement of the ball on the target. A control button to change the difficulty level is also provided in the GUI. A database containing the information about user-id, task completion time, number of errors, score, etc., is created simultaneously during the exercise for further analysis.

The pegboard filling exercise consists of three levels of difficulty with decreasing peg-hole tolerance for higher difficulty levels (see figure 3b). The task is to fill the pegboard with pegs. Visual cues such as color change of pegs, and shadows are provided to help the subjects in completing the tasks. Dropping of the peg before placing it in one of the empty holes is recorded as error and reported with a sound cue and reduction in the score. The time taken to complete the task is displayed on screen and recorded in the database and later used for analysis.

PILOT STUDY ON HEALTHY SUBJECTS

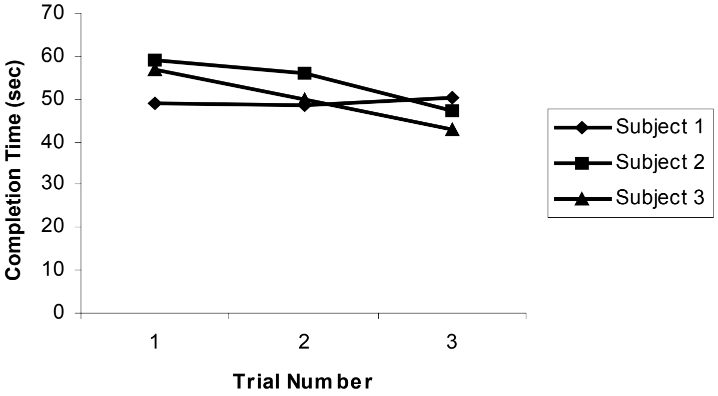


Figure 4. Effect of task learning on completion time over repeated trials for healthy subjects.

A pilot study was done on healthy normal subjects before testing the VR training system on amputees. The pilot study of the rehabilitation system consisted of trials to test the usability of the system. Three normal subjects, two male and one female volunteers, were recruited for the study. Each subject performed three trials with each trial consisting of three difficulty levels and 2 minutes rest period in between. At each difficulty level the task was repeated five times. The order in which targets representing different difficulty levels were presented was kept fixed. Completion time of the individual subjects as a function of trial number (see figure 4) shows a reduction in the time it took to pick up the virtual ball using the sensing sleeve, indicating learning.

The reduction in the average completion time and standard deviation of the group (see figure 5) over repeated trials confirms an improvement in the uniformity among group members.

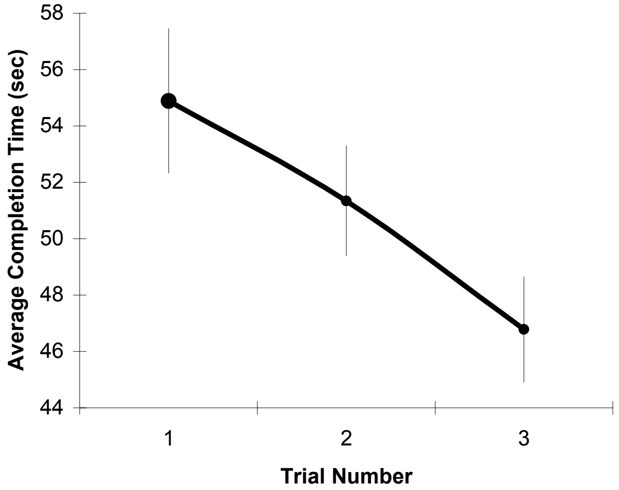


Figure 5. Learning curve for the group of healthy subjects.

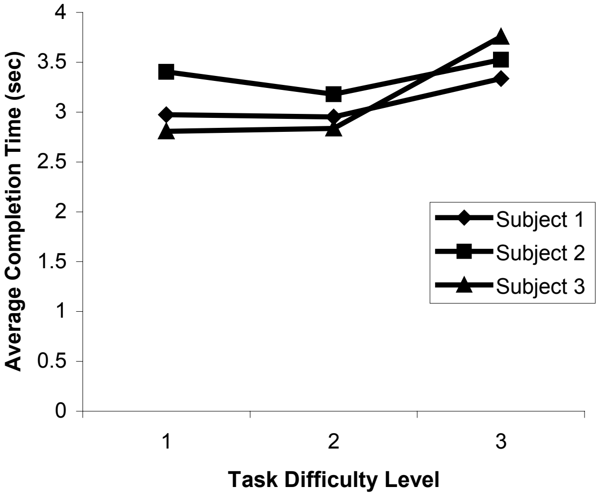


Figure 6. Average completion time as a function of different task difficulty levels.

The database generated during trials stores the completion time for individual task at each difficulty level. From figure 6, it can be noticed that though there is no significant difference in average completion time between difficulty levels 1 and 2, there is an increase in the completion time for difficulty level 3. This could be accounted by the fact that both the difficulty levels 1 and 2 have a target rectangle size larger than the ball diameter. The completion of a task of difficulty level 3 (target size equal to ball diameter) requires better muscle control, as well as better visual acuity and a higher cognitive load. It is thus intuitive that it would take longer to complete it (by as much as 37% for Subject 3).

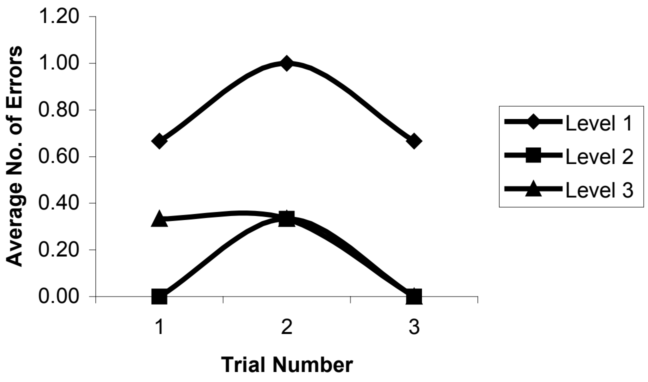


Figure 7. Average number of errors as a function of different task difficulty levels.

Figure 7 graphs the number of errors averaged over the three subjects and trial number. An error was logged when the ball was lost en route to the target, or when it was dropped outside the target area. The shape of the curve for tasks of difficulty 2 shows a reduction in error rate with trial number, indicating the subjects learned with repetition. However, the shape of the curves for the easiest and hardest to perform tasks is unexpected, with a maximum number of errors in the second trial. This unexpected result may be due in part to the small number of subjects used in this pilot study. There are also "hidden" learning effects. The task of difficulty 3 (highest) was always performed last, thus subjects had a chance to learn the system in two previous trials. Probably randomizing the order in which tasks of different difficulty levels were presented would have compensated somewhat for the learning effect noticed in the present data.

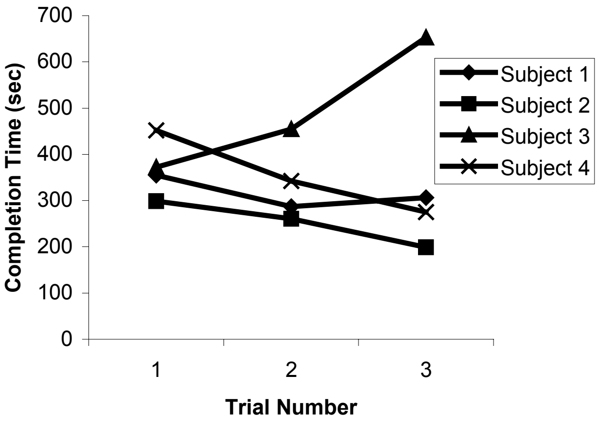


Figure 8. Effects of task learning on completion time (pegboard).

Figure 8 shows the results of the subject trials of pegboard exercise conducted on another set of healthy subjects. The group consisting of four male volunteers was asked to perform three trials of the pegboard exercise with each trial consisting of three levels of difficulty. Reduction in completion time of the whole task in the third trial indicates improvement in the overall performance. However the completion time increased with each trial for one of the subjects (Subject 3) indicates fatigue due to the incompatibility of the sleeve with his anatomy of the hand.

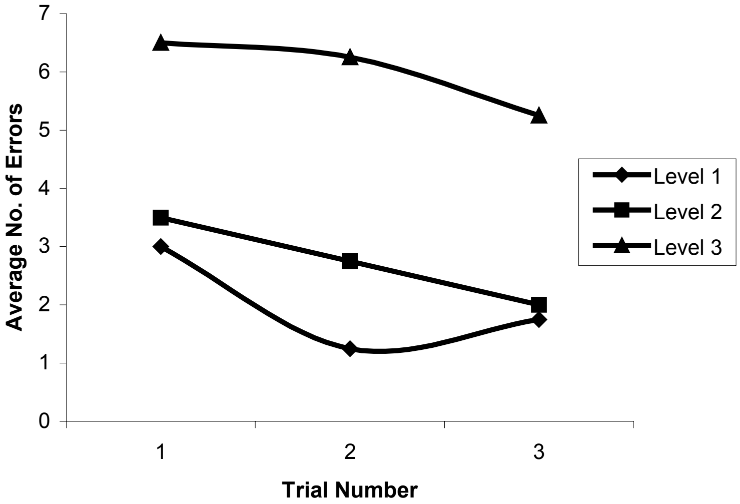


Figure 9. Average error rate as a function of trial number and difficulty level (pegboard).

Analysis of the number of errors recorded in the database during the trials as a function of trial number (see figure 9) also supports the improvement in task performance at each level of difficulty.

EXPERIMENTAL DATA ON AMPUTEES

Figure 10. An amputee subject fitted with the sensing socket performing the VR experiment.

A trans-radial amputee subject was subsequently tested on the VR-based training system. A socket with eight FSRs positioned based on the subject's senses in the residuum was custom made (see Figure 10). This socket replaced the sleeve that was used in the study conducted with able-bodied subjects. The same experimental protocol used for the healthy subjects was followed for the amputee subject with three trials and two minutes rest period intervals. The amputee subject was given training on using the system prior to the trials.

Results of the experiment (see figures 11 and 12) illustrate a significant reduction in completion time over the repeated trials and an increase in average completion time for difficulty level 3. These results matched with those of the pilot study. It was observed that the subject was able to grasp the virtual ball with ease and control. As a consequence he did not commit any errors during the trials, which demonstrated the subject's ability to sustain the grasp.

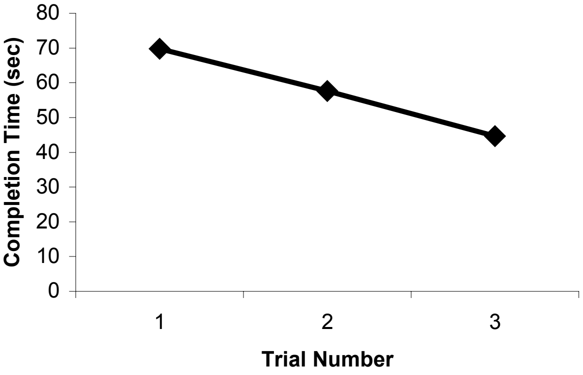


Figure 11. Amputee reduction in the task completion time over the repeated trials.

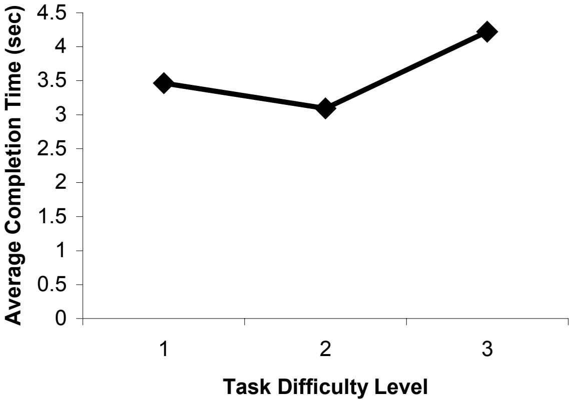


Figure 12. Amputee average task completion time vs. task difficulty level.

Figure 13. Amputee performing the pegboard exercise with sleeve designed for healthy subjects.

Another trans-radial amputee (below wrist) was recruited to perform the pegboard exercise. The results of the trials are shown in the table 1. Only two trials were conducted, as the subject was not able to continue the experiment after the difficulty level 3 of second trial because of physical discomfort. However the data acquired during the trials shows an improvement in the task performance both in terms of completion time and number of errors committed.

Table 1. Task completion time for difficulty levels over two trials (pegboard).

Difficulty Level	Trial 1		Trial 2	
	Completion time (sec)	Number of Errors	Completion time (sec)	Number of Errors
1	321.84	1	265.94	3
2	273.94	11	260.50	6
3	462.94	20	-	-

CONCLUSIONS AND FUTURE WORK

The initial investigation with normal individuals shows encouraging results, in terms of system usability and ability to train in the control of a virtual hand. The visualization of the hand motion in the graphics environment was utilized in determining the faithfulness of the hardware and the filtering program in detecting the actual hand motions.

The pilot study conducted with an amputee subject has provided promising outcomes and insights into the improvement of the system. The initial VR environment was designed for right hand amputees. This provided a minor discomfort for the subject who was a left hand amputee. To address this concern, the graphics software was modified to provide an option to choose the appropriate virtual hand model.

It is expected that the VR based training system for upper-limb amputees in using the myo-kinetic interface can prove as a valuable tool for designing and controlling of the prosthetic hand.

The current sleeve design incorporates eight FSRs for measuring the pressure signals and recognizing the user's hand motions. This makes the placement of the sensors dependent on the individual's specific anatomy. A new sleeve with 16 sensors, which could make the placement of the sensors on the arm independent of the user, is under development.

ACKNOWLEDGMENTS

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