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Manipulation Practice for Upper-Limb Amputees Using Virtual Reality

Abstract

We developed a novel interface that gives upper-limb amputees a virtual hand that can manipulate objects in a challenging environment. The interface registers specific myokinetic activity of the residual limbs, and encodes the intended voluntary movements that are then actualized as virtual hand motions. The composite myokinetic interface-virtual reality (MKI-VR) system consists of an array of pressure sensors mounted in an arm sleeve, sensors of elbow- and shoulder-joint angles, a trained filter derived from the pseudoinverse of a response matrix, and a virtual hand model, programmed in Java 3D. Users can manipulate virtual objects such as balls and pegs in a 3D training environment, while their performance at various difficulty levels is scored. In preliminary tests, upper-limb amputees readily gained the ability to grasp and release virtual objects. We propose the utility of the MKI-VR system both as an assessment tool for rehabilitation engineers, and as a motivator for amputees to exercise and thereby maintain their residual motor ability.

1 Introduction

Robotic hands are becoming increasingly capable of reproducing the function of human hands, and could eventually become substitutes for them as prostheses. The major obstacle for functional hand restoration is therefore not the prosthetic mechanism, but the interface between it and the human (Craelius, 2002). Overcoming this obstacle and developing the proper human-machine interface requires knowing the capabilities of amputees to control a hand. Our previous work has shown that amputees can control simple flexion of multiple fingers (Abboudi, Glass, Newby, Flint, & Craelius, 1999; Phillips & Craelius, in press); however, little else is known about their residual potential and how to exploit it. This report extends our knowledge of the residual abilities of amputees by testing their control over a virtual hand.

Persons with intact forearm residua, having either transradial amputation or congenital defect, retain control apparatus for basic hand functions, because the forearm contains the extrinsic hand muscles controlling finger flexions/extensions and wrist movements. Exploiting this residual functionality is easy for amputees when they are properly interfaced with a mechanical hand (Abboudi et al., 1999); however, due to practical limitations, training for skill and dexterity has thus far been limited to brief laboratory experiences. Virtual reality (VR) opens a much simpler window to the residual control capabilities, principally because it requires no moving parts. VR lets amputees play and

Table 1. *Amputee Information*

	Amputation site	Years since amputation	Arm tested	Condition of residuum	Prosthesis used
Amputee 1	Transradial, 12 cm below elbow	14	Left	Extensive scarring and fatty tissue	Myoelectric
Amputee 2	Transradial, 20 cm below elbow	18	Right	Muscular atrophy and some nerve damage	Body-powered hook

work in a structured 3D world with a reliable hand having an inexhaustible supply of energy. VR not only provides training and rehabilitation possibilities for patients with stroke and amputations (Harvey & Longstaff, 2001; Boian et al., 2002; Merians et al., 2002), it can help engineers design, or "virtually prototype," the next generation of mechanical hands. Moreover, VR visualization of an arm may help relieve phantom pain, if the user can learn to transform his virtual image into a less painful pose (Mooney, 2003).

Herein we describe a novel interface for VR that registers residual kinetic activity of the limb and encodes it to represent the intended motions in a virtual environment.

2 Methods

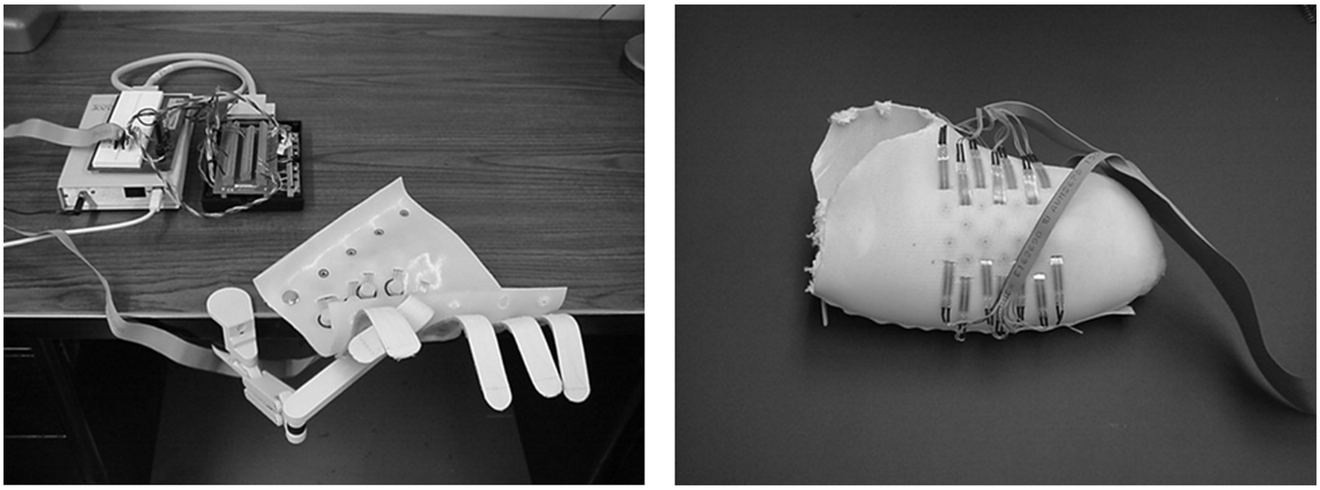
2.1 Human Subjects

Subjects were tested following informed written consent, after approval from the Rutgers University Institutional Review Board. An initial screening exam was performed by questionnaire and by direct palpation of the forearm during requested hand motions. Criteria for acceptance into the study were (1) below–elbow amputation, (2) the presence of afferent and efferent phantom activity, (3) palpable soft-tissue movement in the limb. Two amputees who met the acceptance criteria participated (see Table 1). Both subjects were transradial, one 12 cm below elbow and the other 20 cm below elbow. Both were male and had amputation as a result of traumatic injury. A total of 9 (8 male; 1 female) normal subjects were included as controls for evaluation of the MKI interface (2 control subjects), pick-and-place exercise (3 control subjects) and pegboard exercise (4 control subjects).

2.2 Sensory Interface

Sensory sleeves were fabricated to register superficial limb kinetics consisting of fabric-reinforced silicone sleeves with sensors distributed over the inner surface, as shown in Figure 1. Sleeves were adapted from an earlier design that used pneumatic sensors coupled to pressure transducers (Abboudi et al., 1999). The current sleeves use piezo-resistive force sensing resistors (FSRs; Interlink Electronics), which have advantages over pneumatic sensors, such as better reliability, lower cost, and simpler electronic interface. FSRs are connected to voltage-divider circuits with fixed resistors such that analog force measurements can be made with a data-acquisition system (DaqPad 6020-E, National Instruments). Compliant silicone foam discs are attached to the FSRs to maintain continuous contact with the limb surface. A sleeve assembled for control subjects incorporates 8 FSR sensors opposing the most kinetically active sites on the anterior surface of the forearm (Figure 1a). This generic sleeve was also used for the amputee having a 20 cm below–elbow residuum, with 8 additional sensors added. A custom sleeve was assembled for the amputee having a 12 cm below–elbow residuum, as shown in Figure 1b, instrumented with 32 multiplexed sensors.

A position-tracking device monitored arm position along a single lateral axis or in a 2D plane. An ergonomic armrest (Ergo Rest, Finland) was instrumented with potentiometers at the proximal and distal rotary



(a) (b)

Figure 1. *FSR sensor sleeves: (a) configuration used for control subjects; (b) 32-sensor custom sleeve used for transradial amputee © 2003 Rutgers University. Reprinted by permission.*

joints. Joint angles were calculated in LabVIEW from potentiometer resistance values using three-point calibration. Polar coordinates were calculated by applying the law of cosines to the joint angles and the fixed lengths of the bars, and were converted to Cartesian coordinates. Final coordinates and myokinetic signals were made available in near-real time to the VR simulation software through a National Instruments DataSocket data server (National Instruments, 1999).

2.3 MKI Algorithm

Voluntary movements begin in the motor cortex and travel through central processing circuits, nerves, and muscle, and are expressed as kinetic activity in the residuum. Thus mechanical activity on the residuum surface represents volition after degradation through the entire system. Volition can thus be characterized by a degradation function, and its inverse, a restoration function, can discriminate specific movements.

Volition degradation is characterized by a system of linear equations (Curcie, Flint, & Craelius, 2001)

$$\mathbf{g} = \mathbf{H}\mathbf{f} \tag{1}$$

where $\mathbf{f}$ is a column vector representing intended activity, $\mathbf{H}$ is a matrix of kinetic responses representing volition degradation through the mechanical system, and $\mathbf{g}$ is a column vector of measured kinetic responses. Approximations of $\mathbf{f}$ can be obtained by applying the inverse of the degradation function to the measured responses according to

$$\hat{\mathbf{f}} = \mathbf{H}^{-1}\mathbf{g} \tag{2}$$

To obtain $\mathbf{g}$, subjects are instructed to perform specific hand movements, according to their abilities, while the sensor array measures mechanical activity on the limb surface. Five or more repetitions of each independent volition are performed with moderate intensity, simulating repeated impulses to the system. A response vector is then constructed from the average peak magnitude of the signal measured on each sensor channel. Repeating the process for other independent voluntary movements provides unique response vectors. The response vectors associated with specific voluntary movements form the columns of the kinetic-response matrix **H.** Generally, the number of sensors in the array and the number of independent motions are different, so the response matrix is not square. Therefore, $\mathbf{H}^{-1}$ is the pseudoinverse of $\mathbf{H}$, computed through the singular value decomposition (Strang, 1988) of $\mathbf{H}$.

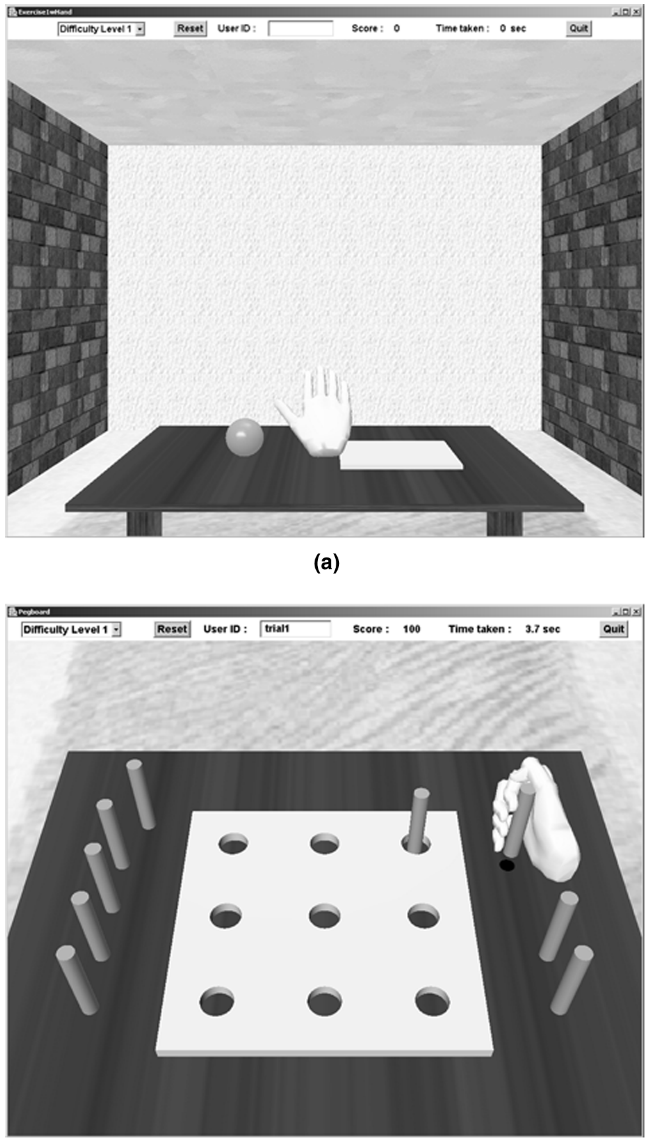
A LabVIEW program performs the data acquisition, filtering, and display of filtered signals. The pseudoinverse filter coefficients are obtained for each subject from an initial training procedure, during which the user is prompted by visible and audible cues to allow baseline measurements and perform multiple repetitions of specific motions. These motions are wrist rotation (supination/pronation), individual finger flexion, or grasping. Upon completion of training, subjects can practice operating a simple hand display that responds to the filtered signals. If the subject loses control of the hand during operation, attempts are made to retrain the filter.

2.4 Virtual Environment

A virtual-reality-based training-exercises simulation was developed using Java3D for rendering and updating the graphic scene. Based on a survey (Atkins, Heard, & Donovan, 1996) of desired activities of people with a transradial amputation, two exercises involving grasping were chosen for training: pick-and-place and pegboard filling. The virtual environment contains a model of a hand (either left hand or right hand) used to interact with the virtual environment. Hand rendering is based on the filtered signals generated by the LabVIEW program, transmitted to Java3D using DataSocket.

The pick-and-place exercise consists of a simple virtual environment with a ball and target located on a table in a virtual room. The task assigned is to pick up the ball with the virtual hand and to place it in a rectangular target area, as shown in Figure 2a. 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 up 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.

The target rectangle changes size depending on level of difficulty of the exercise; the target is set to 3X, 2X, or 1X the ball diameter. Errors are recorded if the ball is dropped off target. Scores are displayed on the screen along with sound feedback to reward the patient for correct placement of the ball on the target. A database containing information about



(a)

(b)

Figure 2. *Virtual-reality exercises to train upper-limb amputees: (a) Pick-and-place exercise; (b) Pegboard exercise. © 2003 Rutgers University. Reprinted by permission.*

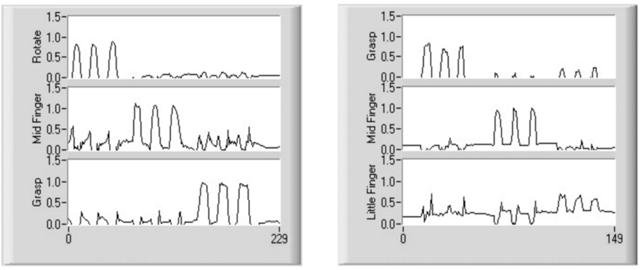


Figure 3. *Filtered data: (left) for control subject; (right) for 12 cm transradial amputee. © 2003 Rutgers University. Reprinted by permission.*

subject-ID, task-completion time, number of errors, and scores is written transparently during the exercise, to allow further data analysis.

The pegboard-filling exercise (seen in Figure 2b) consists of three levels of difficulty with decreasing peg-hole tolerance for higher difficulty levels. The task is to fill the pegboard with nine pegs. Visual cues, such as the color change of pegs and shadows, are provided to help the subjects in completing the task. Dropping of a peg outside the 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, recorded in the database, and later used for analysis.

3 Results

3.1 MyoKinetic Interface

Figure 3 shows typical filtered outputs obtained from a control subject wearing the 8-sensor sleeve and a 12 cm transradial amputee wearing the 32-sensor sleeve. Each plot represents the activity of a particular volitional motion indicated to the side. The ordinates represent the relative intensity of the corresponding volition, scaled from 0 to 1. The abscissae are displayed in terms of number of samples, where both data sets are approximately 10 seconds in duration. Signals along the diagonal, analogous to the diagonal of a matrix, represent correctly identified motions, whereas signals in off-diagonal positions represent coupling between motions.

For the control subject, off-diagonal signals are low relative to the diagonal for both wrist rotation and grasping, indicating minimal interference from other motions. Output from middle-finger flexion is not perfectly discriminatory, however, since it has significant off-diagonal signal. For the amputee subject, grasp and middle flexion show little interference from other motions whereas the output for little-finger flexion exhibits peak off-diagonal values nearly as high as the diagonal. In practice, this coupling of motions results in occasional activation of unintended motions of the virtual hand but does not affect the subjects' abilities to control intended motions. Two control subjects performed three independent motions that were discriminated by the filter: wrist rotation, middle-finger flexion, and grasp. One amputee (12 cm transradial) also performed three perceived motions that were discriminated: grasp, middle-finger and little-finger flexion. Another amputee (20 cm transradial) was able to perform two motions: wrist flexion/extension and wrist rotation.

3.2 Testing Control Subjects

A preliminary study was done on healthy normal subjects before testing the VR training system on amputees. The pilot study consisted of pick-and-place trials to test the usability of the rehabilitation system. Three control subjects, 2 male and 1 female volunteers, were recruited for the study. Each subject performed three trials with each trial consisting of three difficulty levels, with 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.

Average time to complete the ball-placing task, along with the standard deviation, declined slightly during the three trial repetitions, as shown in Figure 4. Completion time was not significantly affected by increasing the difficulty level, although at Level 3, a slight upward trend was evident in the 3 subjects, as shown in Figure 5.

The pegboard exercise was performed by 4 control subjects, whose results are shown in Figure 6. Results were mixed, with 2 of the subjects showing steady improvement in performance (decline in completion time)

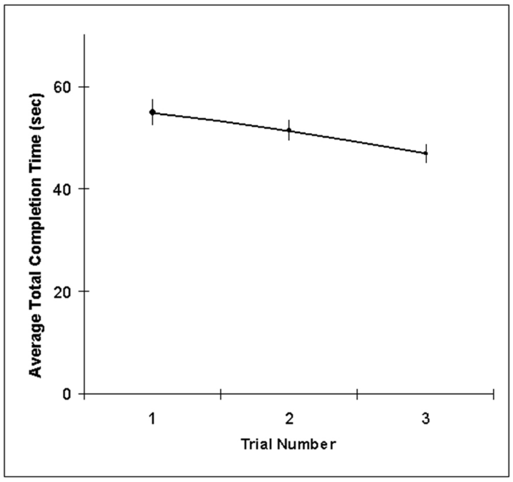


Figure 4. *Learning curve for the group of healthy subjects (n = 3) for the pick-and-place task. © 2003 Rutgers University. Reprinted by permission.*

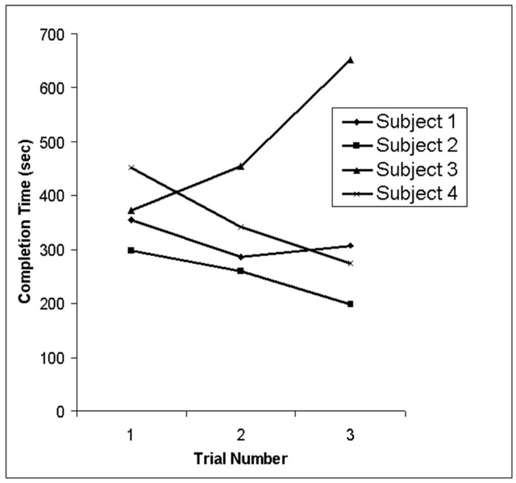


Figure 6. *Effects of task learning on completion time (pegboard). © 2003 Rutgers University. Reprinted by permission.*

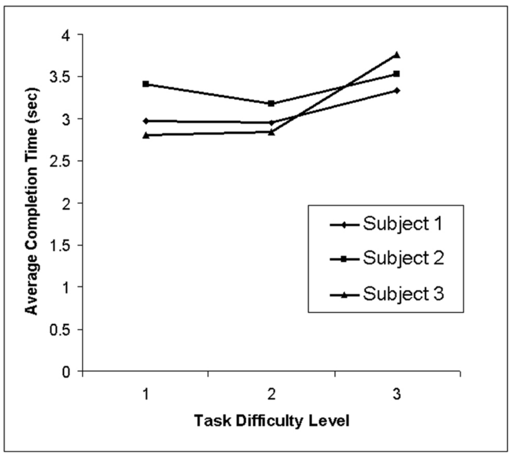


Figure 5. *Average completion time as a function of different task-difficulty levels for pick-and-place. © 2003 Rutgers University. Reprinted by permission.*

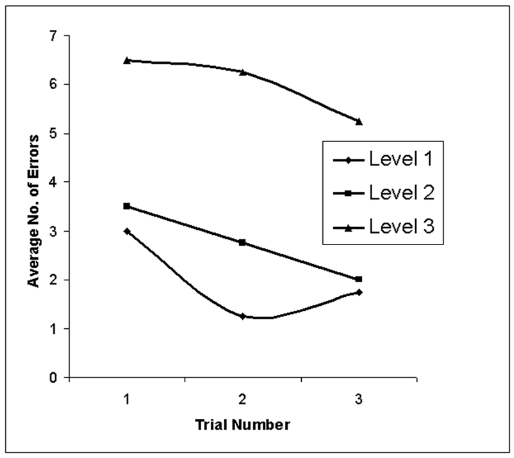


Figure 7. *Average error rate as a function of trial number and difficulty level (pegboard). © 2003 Rutgers University. Reprinted by permission.*

over the three trials, and 1 subject showing no further improvement after the second trial. Subject 1 demonstrated a steady decline in performance, suspected to be the result of poor sensor-sleeve fit due to a comparatively smaller circumference of the forearm. Average error rates increased with difficulty level and declined slightly with repetition, as shown in Figure 7.

3.3 Amputee Subjects

A transradial amputee subject was subsequently tested on the VR-based training system. A sleeve with 32 FSRs positioned over kinetically-active sites of the residuum was custom-made (see Figure 8). The same experimental protocol used for the healthy subjects was

Figure 8. *An amputee subject fitted with sensing socket performing the VR experiment. © 2003 Rutgers University. Reprinted by permission.*

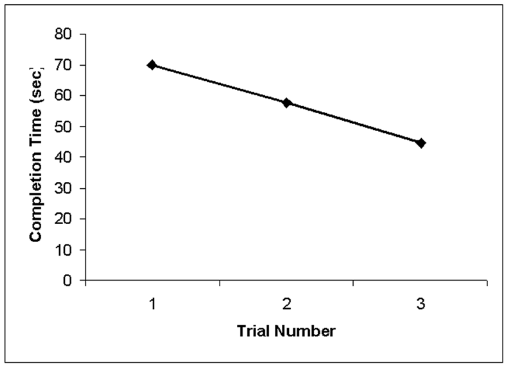


Figure 9. *Amputee reduction in the pick-and-place task-completion time over repeated trials. © 2003 Rutgers University. Reprinted by permission.*

applied to the amputee subject with three trials and 2-minute rest-period intervals. The amputee subject was trained on using the system prior to the trials.

The amputee subject improved his performance over the repeated trials, as shown in Figure 9. It was observed that the subject was able to grasp the virtual ball with ease and control and, in contrast to the control subjects, committed no errors during the trials.

Another transradial amputee (20 cm below elbow) performed the pegboard exercise with results shown in Table 2. Only two trials were conducted, as the subject was not able to continue the experiment after difficulty Level 3 of the second trial because of discomfort. Possible explanations for this discomfort may have been that the subject had atrophied residual muscles, or that the arm-tracking device may have interfered with the ability to accurately place objects. The subject, however, improved during the trials both in terms of completion time and number of errors.

4 Conclusion

We described a pilot system that allows upper-limb amputees to perform simple dexterous tasks in a VR environment using a novel sensory interface. Visualization of hand motion in the graphics environment was utilized to demonstrate the feasibility of using the myokinetic interface and the filtering program for detecting intended hand motions.

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 pilot study conducted with 2 amputee subjects has provided promising outcomes and insights into the improvement of the system. The first VR environment was designed for right-hand amputees. Graphics software was later updated to accommodate left-hand amputees following the session with a left-hand amputee.

The current sleeve design incorporates 8 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. New sleeves with 16 or 32 sensors, which might relax the precision with which sensors must be placed on the forearm, are under development.

The MKI-VR training system should encourage upper-limb amputees to maintain or regain residual motor function that may be useful in controlling future hand prostheses. Future work of this system will involve direct comparisons with conventional myoelectric control systems and implement VR programs

Table 2. *Task-completion Times for Pegboard Task, Amputee Subject #2*

	Trial 1		Trial 2	
Difficulty Level	Completion time (s)	Number of Errors	Completion time (s)	Number of Errors
1	322	1	266	3
2	274	11	260	6
3	463	20	—	—

that take advantage of the subject's ability to control multiple degrees of freedom.

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