2011 IEEE International Conference on Rehabilitation Robotics
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 29 - July 1, 2011

Multi-day Training with Vibrotactile Feedback for Virtual Object Manipulation

Qi An
Department of Precision Engineering
The University of Tokyo
Tokyo, Japan
anqi@robot.t.u-tokyo.ac.jp

Yoky Matsuoka, Cara E. Stepp
Department of Computer Science & Engineering
University of Washington
Seattle, USA
yoky@cs.washington.edu, cstepp@alum.mit.edu

***Abstract*—Optimal function of prosthetic hands for activities of daily living requires knowledge of contact force; however, users of prosthetic hands must rely on visual feedback for object manipulation, requiring constant concentration. Vibrotactile stimulation was explored as a modality for force feedback over multiple testing sessions. Unimpaired participants (N=6) performed virtual object manipulation with their right index finger using both visual feedback and vibrotactile feedback corresponding to the applied force on the virtual object on four days over a 4–8 day period. Object manipulation outcome measures were user difficulty ratings, object displacement, and object average velocity. Participants were able to utilize the vibrotactile feedback to statistically significantly improve performance of all three outcome measures over the four days. Significant improvements in all outcome measures were seen between days 3 and 4, indicating that steady state performance may not have been reached. Results support the use of augmentative vibrotactile feedback for users of prosthetic hands, though future longer longitudinal study will be necessary to determine steady state performance.**

Keywords-prosethetic hand, sensory feedback, vibrotactile stimulation

I. Introduction

Many myoelectric hand prostheses have been developed, but most cannot fully contribute to improvement of prosthesis users activities of daily living due to lack of functional benefit [1]. There are many suggested improvements for hand prostheses, such as weight reduction, lower cost, cosmetic appearance, better control, and force feedback [2]. Force feedback has not been incorporated widely in commercial products. Instead, users must rely mainly on visual feedback for object manipulation, which requires constant concentration. Prosthetic hand users have requested proprioceptive feedback in addition to visual feedback [3], which may alleviate the demands of visual attention and improve the function of hand prostheses. In addition, it has been shown multisensory feedback contributes to body ownership [4], which could contribute positively to users' quality of life.

There is technology available to detect contact force on prosthetic hands and fingers, and this technology has even been incorporated into some prosthetic hands, e.g., the cybernetic hand [5]. A variety of feedback approaches have been suggested [6] [7]; however, given the noninvasive nature of vibrotactile stimulation, feedback through this modality corresponding to the applied force may be a promising approach.

Previous research has been thus far inconclusive about the ability of users to utilize vibrotactile feedback for object manipulation. Although 5 users of myoelectric prosthetic hands were able to reduce the necessary force to grasp an object when using vibrotactile feedback compared visual feedback alone [8], 8 unimpaired subjects using a myoelectric prosthesis simulator were not able to reduce error in a force-matching task using vibrotactile stimulation [9]. No previous study in the area of vibrotactile feedback for object manipulation has tested participants past a single session of interaction, so the role of experience and training on the ability to incorporate vibrotactile feedback for object manipulation is unknown.

In our previous research, we have developed an experimental system using a robotic haptic device to evaluate virtual manipulation using augmentative vibrotactile feedback [10]. In this study, we use this system to evaluate longitudinal effects of vibrotatctile feedback on virtual object manipulation over four sessions on separate days. The objective of this research is to determine whether individuals can improve their ability to use vibrotactile feedback to manipulate a virtual object over multiple sessions.

II. Methods

A. Experiment Overview

Our previously developed virtual object manipulation task and system were used to test the longitudinal effects of vibrotactile feedback. Participants of the experiment (N=6) performed a virtual object manipulation task in which vibrotactile force feedback was essential; participants were asked to apply appropriate normal force to a virtual object (box) to allow for translation, and to drag it to a target as quickly as possible without breaking it. This task was chosen to be easy to understand, functional, and relatively difficult to perform without sensory feedback. It was inspired by the difficulties of prosthetic hand users with appropriately applying normal force to delicate objects such as a disposable plastic cup. Performance of participants was measured in terms of difficulty ratings by participants, total box displacement, and average box velocity for each trial. For every participant, the

This study was funded in part by a Walter C. and Anita C. Stolov Research Fund Grant.

978-1-4244-9862-8/11/$26.00 ©2011 IEEE

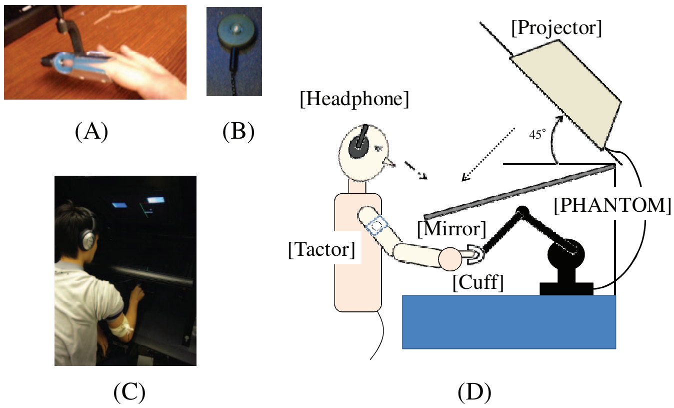

Figure 1. (A) Participants placed their index finger in a custom cuff. (B) C2 tactor. (C) Photograph of the experimental set-up. (D) Schematic of the experimental projection system and PHANTOM device to measure movement of the finger.

experiments were performed in four sessions on four different days within a 4 – 8 day period.

B. *Virtual Task System*

The experimental system was used to measure the movement of the participant's finger and to display the virtual environment to the user in real time. Finger position was measured with a PHANTOM Premium 1.0 robotic device (Sensable Technologies, Inc., Woburn, MA). The index finger was coupled to the manipulator of the robotic device with a custom finger cuff (Fig. 1-A). Although participants could move their finger freely due to the three active degrees of freedom of the device, only the movement of horizontal and vertical directions were used in the experiment. The virtual environment, including the movement of the participant's index finger, was projected by inverted monitor placed at 45º toward them. Participants could observe the image from a mirror set above the virtual task space of PHANTOM robotic device (Fig. 1-D).

Vibrotactile feedback was supplied to the user with a C2 tactor (Engineering Acoustics, Inc.; see Fig. 1-B). The tactor was attached to the participant's upper right arm with an elasticized cloth bandage (Fig. 1-C), and it could provide vibrotactile feedback. The vibrotactile stimulation was provided at 250 Hz, the frequency at which glabrous skin has been shown to be maximally sensitive to detection [13] [14].

During experimentation, participants wore noise canceling headphones (Bose, Framingham, MA) which were used to present the auditory stimuli for the cognitive test (described in the following section) and low-level masking noise. Masking noise and noise-canceling headphones were used to prevent noise from vibrotactile stimulation from being used as task-relevant feedback.

C. *Task*

1) *Virtual Object Manipulation*

During the experiment, participants were shown the virtual environment. Screenshots of the environment are shown in Fig. 2. The white sphere indicated participant fingertip position and moved vertically and horizontally in the virtual environment according to the vertical and horizontal movement of their index finger. Participants were asked to move the box to the target as quickly as possible without breaking it.

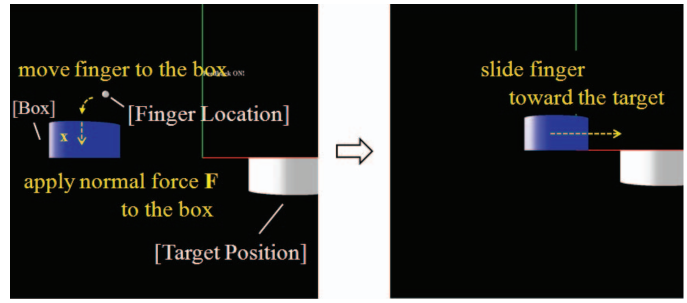

Figure 2. (Left Panel) Screen shot showing the initial screen image of the experiment. The white sphere corresponds to fingertip movement. In order for participants to apply normal force to the box, the finger had to be moved into the box. (Right Panel) Screen shot illustrating movement of the box toward the target position. The white ball is inside the box, and both deformation of the box and the white ball cannot be seen.

In order to move the virtual object, the participant had to apply appropriate normal force to the top of the object and drag it from its initial position at the left of the virtual space toward target position on the right. To do so, the participant had to move their finger in the right horizontal direction while applying a normal force greater than a threshold for overcoming friction to move (F_{move}), but without creating a normal force greater than the threshold for breaking the box (F_{break}). If the applied normal force was smaller than F_{move}, their finger slipped without moving a box. Forces greater than F_{break} would cause the box to break. Two types of boxes were used and were differentiated by color, blue and red. These boxes had different stiffness characteristics, both of which were scaled versions of measured stiffness of a disposable plastic cup. The normal force for each box was calculated as two continuous piecewise functions shown in eq. (1) and (2) where x is a finger displacement from top surface of each box measured in centimeters.

$$F_{blue}(x) = \begin{cases} (0.34\,\mathrm{N/cm})x, & \text{if } x < 1.7\ \mathrm{cm} \\ (4.65\,\mathrm{N/cm^2})x^2 - (14.33\,\mathrm{N/cm})x + 11.55, & \text{if } x > 1.7\ \mathrm{cm} \end{cases}$$

$$F_{red}(x) = \begin{cases} (0.68\,\mathrm{N/cm})x, & \text{if } x < 1.7\ \mathrm{cm} \\ (9.59\,\mathrm{N/cm^2})x^2 - (30.67\,\mathrm{N/cm})x + 25.56, & \text{if } x > 1.7\ \mathrm{cm} \end{cases}$$

F_{move}, the threshold for moving the object, was arbitrarily set as $F_{move} = 1.2 \times F_{blue,red}(1.7cm)$, and F_{break}, the threshold for breaking the object, was defined as $F_{break} = F_{move} + 0.75N$. Despite the constant force window of 0.75N, due to their different stiffnesses, the tolerant displacements for each box differed (2.7 mm for the blue box and 1.6 mm for the red box). Each trial ended at the time when the box reached at the target position (30cm right from the initial box position) or when the box was broken.

Deformation of the box during manipulation was not shown (see Fig. 2). Similarly, the fingertip position (white ball) was occluded by the box. Thus, participants could not determine the amount of force applied to the box using visual feedback alone. Vibrotactile stimulation was provided by the C2 tactor, with vibrotactile amplitudes corresponding linearly to the virtual normal force.

2) Cognitive Task

During half of the trials, participants were asked to perform a simultanous cognitive task during object manipulation. The task used was an auditory 2-back test [15]. They listened to 16 digit strings of numbers, and were asked to identify verbally all numbers repeated with only one intervening number. Participants did not always hear all 16 digits during trials since trials were of variable length. This cognitive load was used to simulate use of a prosthetic device in the face of the simultaneous cognitive demands of daily life. Before starting the experiment, all participants practiced 24 sets of the cognitive task to ensure that they could comfortably and correctly perform it

D. Experimental Protocol

The experiment was conducted on four sessions on four separate days over a 4 – 8 day period. Participants performed 40 trials in each session. The trials for each session consisted of 10 sets of four trials presented in random order: blue box with cognitive test, red box with cognitive test, blue box without cognitive test, and red box without cognitive test.

During the experiments, participants sat in a chair resting their right forearm so that they could move their right index finger freely. After every trial they were asked to specify how difficult the task was. Difficulty was rated between 1 – 5 where 1 was the easiest and 5 was the most difficult.

E. Participants

There were 6 participants (1 male, 5 females; average age = 23.0 years, STD = 3.5 years). All participants were right-handed with no known problems with their hand. Consent was obtained from all participants in compliance with the Institutional Review Board of the University of Washington.

F. Data Analysis

Performance of each participant was evaluated by the following outcome measures: difficulty rating, box displacement (the total distance that the box moved toward the target position in each trial), and average box velocity (total box displacement normalized by trial duration time). A three factor repeated measures analysis of variance (ANOVA) was performed to assess the effects of box type (blue or red), cognitive task (on or off), and day (days 1 – 4), with *post hoc* two-sided Tukey's Simultaneous tests when appropriate. In order to evaluate statistical significance, significance level was set to $p = 0.05$.

III. RESULTS

Effects of box, cognitive task, and day are shown in Table I in terms of mean and standard error. Based on the results of the ANOVA on box difficulty ratings, two-sided Tukey's Simultaneous tests were used to test the effects of box type, cognitive test, and day. Compared to the red box, trials with the blue box showed a statistically significant decrease in difficulty ratings, increase in total displacement, and increase in average box velocity. Trials during the cognitive task showed statistically significantly increased difficulty ratings, decreased total displacement, and decreased average velocity of box movement relative to trials without a simultaneous cognitive task.

TABLE I

	Difficulty		**Displacement (cm)**		**Velocity (cm/s)**	
	Mean	***SE***	***Mean***	***SE***	***Mean***	***SE***
Box: Blue	3.26	0.04	18.71	0.57	0.52	0.01
Box: Red	3.86	0.03	8.49	0.47	0.24	0.01
Cognitive Test: OFF	3.45	0.04	14.38	0.58	0.40	0.01
Cognitive Test: ON	3.66	0.04	12.83	0.56	0.35	0.01
Day: 1	3.85	0.05	5.18	0.57	0.21	0.02
Day: 2	3.52	0.06	13.91	0.79	0.35	0.01
Day: 3	3.60	0.05	16.78	0.80	0.43	0.02
Day: 4	3.25	0.06	18.57	0.76	0.51	0.02

Means of the three performance outcome measures as a function of day are shown in Fig. 3. Difficulty ratings were statistically significantly decreased between day 1 and day 2, and between day 3 and day 4. Over the four days, difficulty ratings were decreased from 3.85 to 3.25 (15% decrease). Average total displacement was statistically significantly increased between day 1 and day 2, between day 2 and day 3, and also between day 3 and day 4. Over the four days, the average total displacement was increased from 5.18 cm to 18.57 cm (259% increase). Finally, average velocity was statistically significantly increased between day 1 and day 2, between day 2 and day 3, and between day 3 and day 4. Average velocity increased from 0.21 cm/s on day 1 to 0.51cm/s on day 4 (139% increase).

IV. DISSCUSSION

The vibrotactile feedback employed in this study showed strong positive effects on user performance of delicate object manipulation as a function of training time. Participants could continue to improve their object manipulation ability over 4 days, and the significant increase in performance between days 3 and 4 indicates that their performance did not reach steady state performance within the 4 days of experimentation. Training using a cross-modality sensory substitution paradigm (electrotactile stimulation for visual perception) has shown improvements in perceptual task performance and changes in brain activation with 7 hours of training applied over 7 days [16]. Thus, longer longitudinal investigation may be needed to determine the maximum user performances and the training time necessary to reach steady state performance; however, the current results are encouraging for the utilization of vibrotactile feedback for long-term use. The strong learning effect observed in the current study suggests careful interpretation of previous short-term research into the area of sensory feedback for prosthetic hand users, and may explain the lack of overall agreement.

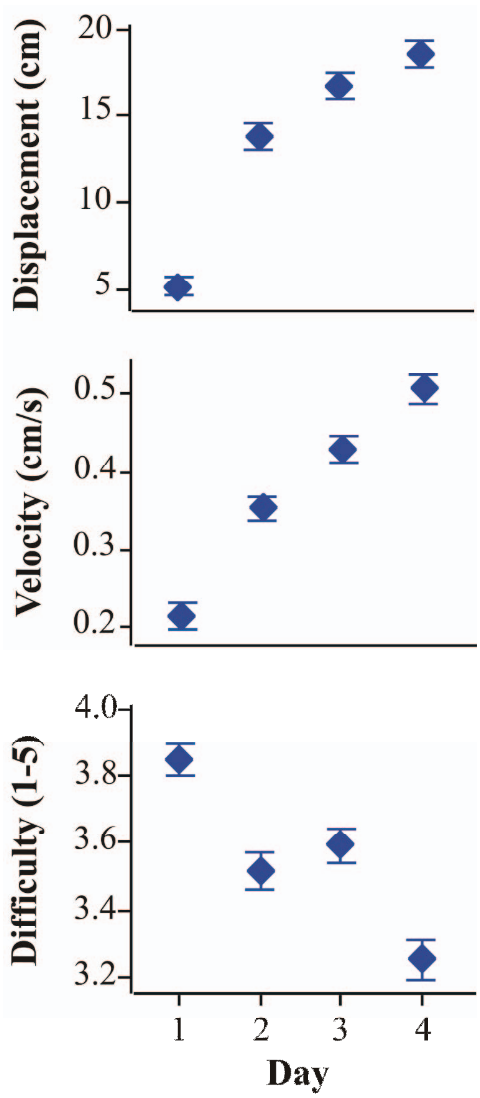

Figure 3. Mean performance outcome measures as a function of day. Error bars indicate +/- SE.

The learning seen over time in the current study is incongruent with previous longitudinal study of vibrotactile feedback for manipulation of delicate objects in a virtual environment [17]. In a previous study, participants utilized augmentative visual, auditory, and vibrotactile feedback proportional to grasp pressure to perform a pick and place task of a delicate virtual object in 3 days of training. Although users were able to perform the task with decreased completion time using vibrotactile feedback than without, positive training effects were not seen [17]. In fact, after 3 days of training, users tended to exert more forces unnecessarily on an object [17]. However, this previous research utilized multiple modes of augmentative feedback in which force was explicitly represented [17], unlike the case where information about force is not available through other modalities as in the current experiment. The explicit representation of force by multiple modalities may have lessened the impact of vibrotactile stimulation as well as increasing overall performance such that user performance may have reached steady state more quickly. Future study comparing longitudinal performance with single and multiple modalities with this experimental paradigm is also warranted.

Although all performance outcomes in the present study showed improvement, decreases in user ratings of difficulty were less pronounced than in the objective measures of task performance of box displacement and velocity. For instance, the average difficulty rating decreased by 15% over the four days, while box displacement and velocity increased by 259% and 139% from day 1 to day 4, respectively. Thus, even though participants showed substantial gains in their objective ability to perform the task, their subjective interpretation was that the task became only marginally easier. One possibility is that doing a difficult object manipulation task without typical direct haptic feedback is so unnatural that the perception of difficulty surpasses task performance. Individuals in the amputee population may be more acclimated to the challenges of performing object manipulation, making them more subjectively amenable to rate decreases in difficulty. Future work to test vibrotactile stimulation in a population of amputees may elucidate this difference between objective and subjective measures.

Statistically significant effects of both box and cognitive task were found for all three performance outcome measures, agreeing with previous study using this system [10]. The simultaneous cognitive task increased difficulty ratings, and decreased box displacement, and average velocity. Due to the larger tolerant band in vertical finger displacement, trials with the blue box were scored significantly less difficult, and resulted in increased box displacement and average box velocity than did the trials with the red box. As described in the methods, the amplitude of vibration was mapped linearly to the virtual normal force. Subjects were not made explicitly aware of the maximum vibration threshold at the F_{break}, but learned this relationship over time through experience with the virtual task. An interesting future question will be whether sensory substitution task experience without a motor component is as effective as learning the relationship between the different intensities of vibration mapping through motor task performance as was accomplished here.

V. Conclusion

Experiments of virtual object manipulation with vibrotactile force feedback were conducted across four different days for 6 participants. Using the vibrotactile feedback, participants were able to statistically significantly improve object manipulation over the four sessions as measured by all three performance outcome measures: difficulty ratings were decreased 15%, average box displacement was increased 259%, and average velocity was increased 139%. However, all outcome measures showed statistically significant increases between experiment days 3 and 4, suggesting that steady state performance was not achieved within the four sessions. These results support the application of vibrotactile feedback in order to enhance manipulation ability of prosthetic hand users. Our future work will include longer longitudinal investigation to determine the maximum steady state performance possible and the necessary training time to achieve that performance.

ACKNOWLEDGMENT

The authors thank Kristina Huynh.

REFERENCES

[1] Dipak Datta, Kanther Selvarajah, and Nicola Davey, “Functional outcome of patients with proximal upper limb deficiency-acquired and congential”, Clin Rehabil February 2004 18: 172-177

[2] Pylatiuk, Christian and Schulz, Stefan and Doderlein, Leonhard, “Results of an Internet survey of myoelectric prosthetic hand users”, J Prosthetics and Orthotics International, vol. 31, pp. 362-370, 2007

[3] Biddiss, Elaine and Beaton, Dorcas and Chau, Tom, “Consumer design priorities for upper limb prosthetics”, J Disability & Rehabilitation: Assistive Technology, vol. 2, pp. 346-357, 2007

[4] H. Henrik Ehrsson, Nicholas P. Holmes, and Richard E. Passingham, “Touching a Rubber Hand: Feeling of Body Ownership Is Associated with Activity in Multisensory Brain Areas”, J. Neurosci.,;vol. 25, pp. 10564 – 10573, 2005

[5] Zollo, L. Roccella, S., Guglielmelli, E., Carrozza, M.C., Dario, P., “Biomechatronic Design and Control of an Anthropomorphic Artificial Hand for Prosthetic and Robotic Applications”, *Mechatronics, IEEE/ASME Transactions on,* vol.12, no.4, pp.418-429, 2007

[6] P.J. Agnew and G. F. Shannon, “Training program for a myo-electrically controlled prosthesis with sensory feedback system”, Am J Occup Ther, vol. 35, pp. 722-727, 1981

[7] H. Schmidle, “The importance of information feedback in prostheses for the upper limbs”, Prosthetics and Orthotics International, vol. 1, no. 1, pp. 21-24, 1977

[8] C. Pylatiuk, A. Kargov, S. Schulz, “Design and Evaluation of a Low-Cost Force Feedback System for Myoelectric Prosthetic Hands”, Journal of Prosthetics and Orthotics, vol. 18, pp. 57-61, 2006

[9] A. Chatterjee, P. Chaubey, J. Martin, and N. Thakor, “Testing a prosthetic haptic feedback simulator with an interactive force matching task”, J Prosthet Orthot, Vol. 20, pp. 27-34, 2008

[10] C. E. Stepp and Y. Matsuoka, “Remote vibrotactile feedback improves object manipulation performance but without faster execution”, presented at 32nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Buenos Aires, Argentina, 2010

[11] L. A. Miller, R. D. Lipschutz, K. A. Stubblefield, B. A. Lock, H. Huang, T. W. Williams III and R. F. Weir and Todd A, Kuiken, "Control of a Six Degree of Freedom Prosthetic Arm After Targeted Muscle Reinnervation Surgery", vol. 89, no. 11, pp 2057-2065, 2008

[12] W. K. kirchner, “Age differences in short-term retention of rapidly changing information”, J Exp Psychol, vol. 55, pp. 352-358, 1958

[13] R. T. Verrillo, “Vibration Sensation in Humans”, Music Perception, vol. 9, pp. 281-302, 1992

[14] R. T. Verrillo, “Subjective Magnitude Functions for Vibrotaction”, IEEE Trans Man mach Syst, vol. 11, pp. 19-24, 1970

[15] W. K. Kirchner, "Age differences in short-term retention of rapidly changing information," J Exp Psychol, vol. 55, pp. 352-8, Apr 1958.

[16] M. Ptito, S. M. Moesgaard, A. Gjedde, and R. Kupers, "Cross-modal plasticity revealed by electrotactile stimulation of the tongue in the congenitally blind," Brain, vol. 128, pp. 606-14, Mar 2005.

[17] C.T. Li, R Kazman, “Vibrotactile feedback in delicate virtual reality operations”, ACM Multimedia 96, pp. 243-251, Boston MA USA, 1996