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Vibrotactile feedback aids EMG control of object manipulation

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***Abstract*—We have previously shown that augmentative vibrotactile feedback can improve performance of a virtual object manipulation task using the finger. Here we studied the effects of vibrotactile feedback using instead electromyographic (EMG) control of object manipulation in N=6 healthy participants. Results showed that users were able to increase performance on an object manipulation task via EMG control when given augmentative vibrotactile feedback. Performance showed a strong effect of learning, which indicates further promise for utilization of this method in prosthetic hand users.**

I. Introduction

THE majority of users of prosthetic hands are limited to the use of visual feedback alone for prosthesis control. Providing augmentative sensory information such as contact force to users of prosthetic hands has the potential to improve their prosthesis control [1, 2] and quality of life [3, 4]. Although it is currently possible to sense fingertip forces in real-time [5-9], how to optimally provide feedback to users is still an open question.

Vibrotactile stimulation for feedback is cheap, non-invasive, and could be easily implemented into existing prosthetic technologies [10, 11]. We have previously used a robotic and virtual interface in which visual and haptic feedback can be experimentally controlled [12] to quantitatively examine and compare methods of delivery. We have found that unimpaired individuals can learn to use a combination of visual feedback and force-based amplitude-modulated vibrotactile feedback to complete an object manipulation task with increased performance than with vision alone [13]. However, a previous study by Chatterjee et al. found that vibrotactile stimulation on the upper arm during use of a myoelectric prosthesis simulator to complete an interactive force-matching task, did not result in a consistent overall reduction in force-matching error [14]. Chatterjee et al. did not use amplitude-modulated feedback but instead represented force by modulating the pulse rate of a square wave, using a 200-Hz carrier frequency.

The goal of this study is to characterize the effect of adding force-based amplitude-modulated vibrotactile feedback to visual feedback for individuals using electromyography (EMG) to complete a virtual object manipulation task. Based on our previous findings [13], we hypothesized that the addition of vibrotactile feedback would increase manipulation performance and that performance would be decreased during a simultaneous cognitive task. The incorporation of EMG to our virtual interface allows for analogous experiments with amputees in the future.

II. Virtual Myoelectric Prosthesis Design

A. Task and Virtual Environment

The task was to apply appropriate normal force to a virtual object to allow for its translation, and to drag it to a target as quickly as possible without breaking it. This task was chosen due to the known difficulty of appropriately applying normal force to delicate objects using a prosthetic hand, such as picking up and manipulating a disposable plastic cup [18].

A video monitor was faced 45° toward the participant with a mirror between the virtual environment and the monitor to reflect images from the monitor to the user (see Fig. 1 lower left panel). Participants interacted with the virtual environment through their forearm EMG and horizontal arm motion. Participants sat in front of the projection system with their right arm extended parallel to the floor and a rolling support under their wrist to allow free movement about the 3D workspace without causing fatigue from holding the weight of their arm. The virtual environment was programmed in C++, with graphics driven by OpenGL.

At the start of the task, one of two possible virtual objects appeared at the left end of the workspace (see Fig. 1). The top of each object (box) was programmed with distinct stiffness characteristics based on a fit to the empirically obtained force-displacement curve acquired during pushing on a disposable plastic cup. The difference between the two boxes and was signaled to the participant by box color (red or blue). The virtual normal force of the blue box, F_{blue} (1), and the red box, F_{red} (2), were defined with x as the displacement of the finger into the box in the normal direction, in centimeters.

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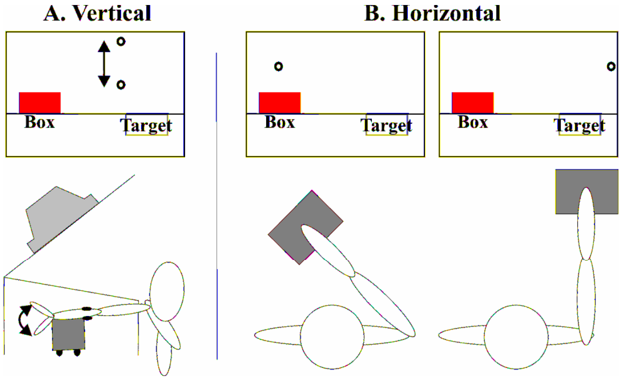

Fig. 1. Control of Virtual Finger Position. Vertical position in the virtual environment was a function of EMG collected during wrist flexion and extension (Panel A). Horizontal position was based on the shoulder angle (Panel B) measured via magnetometer.

$$F_{blue} = \begin{cases} (0.34\text{N/cm})x, & \text{if } x < 1.7\,\text{cm} \\ (4.65\text{N/cm}^2)x^2 - (14.33\text{N/cm})x + 11.55, & \text{if } x > 1.7\,\text{cm} \end{cases} \quad (1)$$

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

The virtual force required to overcome friction to translate each box, F_{move}, was defined as 1.2 times the virtual force at the displacement of 1.7cm. The virtual force threshold to "break" each box, F_{break}, was defined as 0.75N greater than F_{move}. Application of virtual normal forces between F_{move} and F_{break} allowed the participant to slide the object to a target located 30 cm to the right of the workspace. The difference in stiffness between the two boxes resulted in different allowable displacements of the finger during motion (1.6 mm for the red box and 2.7 mm for the blue box) in the direction of the virtual normal force.

During the task, users received real-time visual feedback of the location of their "finger" in the virtual environment and the position of the box (see Fig. 1). The virtual finger position was indicated by a small sphere. Finger location was occluded during penetration of the box, and deformations of the box were not shown.

B. Electromyographic Control

The control of the finger in the vertical direction of the virtual environment was determined via two surface EMG signals. The two differential EMG signals were acquired at 1000 Hz using a data acquisition card.

The y-direction velocity was defined as the difference between the root-mean-square (RMS) of the two signals, multiplied by a scaling factor. EMG signals were differenced such that greater muscle activity for wrist extension caused an increase in the upward velocity of the finger in the virtual environment, and greater wrist flexion caused an increase in the downward velocity. The RMS was calculated in 300 ms (300 samples) windows with 90% overlap. Because the voltage measured at the skin surface can vary widely between individuals due to differences in muscle activation, electrode contact, and subdermal fat, the scaling factor was defined independently for each participant. The scaling factor was determined by averaging the individual's maximum sEMG during wrist extension and flexion as in (3).

$$\text{Scaling Factor} = \frac{2.1}{2}\left(\max\left(EMG_{extension}\right) + \max\left(EMG_{flexion}\right)\right) \quad (3)$$

The constant 2.1 was chosen empirically to provide a comfortable virtual vertical velocity.

C. Magnetometer Control

The control of the horizontal virtual finger position was determined via a Honeywell HMC6352 electronic compass, which measured compass heading at 20Hz with 0.5° resolution. The magnetometer measurement was read by a Microchip PIC18F14K22 microcontroller over an I2C bus, which translated the heading angle at 8 kHz into a hardware-controlled 10-bit pulse-width-modulated signal with duty cycle proportional to the measured angle, which was acquired using a data acquisition card.

The angle measured by the magnetometer was averaged over every 235 samples (30 ms) and then scaled such that possible arm angles corresponded with the horizontal width of the virtual environment. An x-position at the far right of the virtual environment corresponded to when the participant's arm was stretched in front making a 90° angle with the participant's coronal plane. Individuals were easily able to rotate their arm counter-clockwise to reach the far left of the virtual environment (see Fig. 1 Panel B).

The horizontal finger motion in the virtual environment was smoothed using a discrete-time exponentially-weighted moving average filter. The cutoff frequency was chosen empirically to be 26 Hz optimize smoothness in the virtual environment and to limit delay.

III. Experimental Methods

A. Participants and Conditions

Participants were 6 right-handed adults (4 male, 2 female; mean age = 23.5 years, SD = 1.6 years). All individuals reported normal hand function. Informed consent was obtained from all participants in compliance with the Institutional Review Board of the University of Washington.

Over approximately 1.5 – 2.5 hours (including breaks), each participant completed 80 trials of interaction with the system. Each participant completed 5 blocks of 16 trials, randomized within block by feedback condition (vision alone, vision + vibrotactile), cognitive load (on, off), and box (blue, red). Trials ended when the box reached the target or was broken. Participants were encouraged to take breaks between any trials to avoid fatigue.

Noise-canceling headphones (Bose, Framingham, MA) were used to present the stimuli for the cognitive task, and to provide low-level masking noise. Since the vibrotactile feedback provided at 250Hz is in the range of human hearing, the noise-cancellation and masking noise were used to ensure that participants were not using any auditory feedback from the tactor to complete the motor task.

Surface EMG was recorded using a 2-channel Bagnoli system (Delsys™ Inc, Boston, Massachusetts) with 2 Delsys™ 2.1 differential surface electrodes placed on the forearm over the extensor carpi radialis (wrist extensor) and palmaris longus (wrist flexor) muscles, referred to as EMG1 and EMG2. A ground electrode was placed on the superior aspect of the participant's right shoulder. EMG signals were pre-amplified and filtered using the Delsys™ Bagnoli system set to a gain of 1000, with a band-pass filter with roll-off frequencies of 20 and 450 Hz.

B. Vibrotactile Feedback

Vibrotactile stimulation was provided using a C2 tactor (Engineering Acoustics, Inc.) mounted to the right lateral upper arm and secured with an elasticized cloth bandage. A 250-Hz carrier frequency was used because human glabrous skin has been shown to be maximally sensitive to vibrotactile stimulation at this frequency [15, 16]. Increases in virtual normal force were translated into increases in the amplitude of continuous vibrotactile stimulation.

C. Cognitive Load

An auditory 2-back test [17] was used as a simultaneous cognitive load during the motor task. The test consisted of auditory presentation of a 1 Hz string of 16 random digits during which participants were asked to respond verbally to identify any numbers repeated with only one intervening number.

Participants practiced 20 sets of the cognitive task without simultaneous interaction with the virtual environment to ensure that they understood the task. During the experiment, participants were asked to complete the cognitive task while simultaneously interacting with the virtual environment.

D. Analysis

Object manipulation performance variables were box displacement (total distance toward the target that participants were able to translate the box during the trial) and average box velocity (box displacement normalized by trial duration). Box displacement and velocity for each trial were calculated using MATLAB (Mathworks, Natick MA).

Statistical analysis was performed using Minitab Statistical Software (Minitab Inc., State College, PA). A 4 factor repeated measures analysis of variance (ANOVA) was performed to assess the effects of feedback (vision alone, vision + vibrotactile), cognitive task (on, off), presentation order (block), and box (red, blue), as well as the interactions of feedback × block, cognitive task × feedback, and block × cognitive task on box displacement and velocity. *Post hoc* two-sided Tukey's Simultaneous tests were performed as appropriate. Statistical analyses were performed using an alpha level of 0.05 for significance.

IV. Results

Out of 480 combined trials, participants were able to successfully move the box to the target 54 times (11% of attempts). During these successful attempts, the average distance achieved was the full range of the task (30 cm) and the average velocity was 1.73 cm/s (SE = 0.14 cm/s). During unsuccessful attempts, the average distance achieved was 2.53 cm (SE = 0.28 cm) and the average velocity was 0.10 cm/s (SE = 0.01 cm/s). Results of ANOVAs for box displacement and velocity are shown in Tables I and II. Fig. 2 shows plots of the primary experimental findings.

TABLE I
Box Displacement ANOVA

Factor	DF	F	*p*
Feedback	1	17.14	<0.001*
Cognitive Task	1	0.20	0.653
Block	4	11.29	<0.001*
Box	1	10.24	0.001*
Feedback × Block	4	1.79	0.129
Cognitive Task × Feedback	1	0.27	0.601
Block × Cognitive Task	4	0.48	0.75

TABLE II
Box Velocity ANOVA

Factor	DF	F	*p*
Feedback	1	7.64	0.006*
Cognitive Task	1	4.49	0.035*
Block	4	10.26	<0.001*
Box	1	12.42	<0.001*
Feedback × Block	4	2.39	0.050*
Cognitive Task × Feedback	1	0.01	0.943
Block × Cognitive Task	4	0.96	0.427

Although feedback, block, and box type all had statistically significant effects on box displacement, no effect of the cognitive task was found. No significant interactions were seen between cognitive task, feedback, and block. *Post hoc* testing showed that the addition of vibrotactile feedback lead to an increase in average box displacement to 7.17 cm (SE=0.73 cm) relative to 4.05 cm (SE=0.56 cm) with vision alone. In addition, box displacement tended to increase as a function of block. Fig. 2 marks the significant comparisons. Further, participants were able to move the blue box significantly further (MEAN=6.82 cm, SE=0.71 cm) than the red box (MEAN=4.41 cm, SE=0.60 cm).

All factors had a statistically significant effect on the box velocity. There was no significant interaction between the cognitive task and block or between the cognitive task and the feedback; however, there was a significant interaction between feedback and block. *Post hoc* testing indicated that the addition of vibrotactile feedback significantly increased box velocities from 0.22 cm/s (SE=0.04 cm/s) to 0.35 cm/s (SE=0.04 cm/s). Addition of a simultaneous cognitive task significantly decreased velocities from 0.33 cm/s (SE=0.05 cm/s) to 0.23 cm/s (SE=0.04 cm/s). Presentation order (block) had a significant effect on box velocity, with velocities increasing as a function of block (see Fig. 2). Lastly, participants were able to move the blue box (MEAN=0.37 cm/s, SE=0.05 cm/s) with greater velocities than the red box (MEAN=0.20 cm/s, SE=0.03 cm/s).

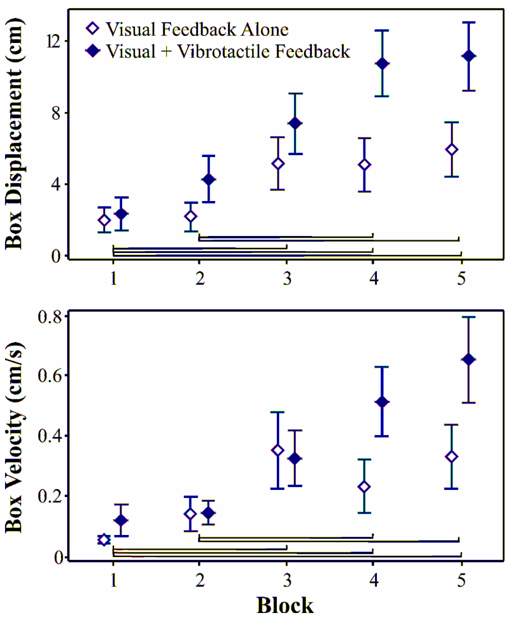

Fig. 2. Primary Experimental Results. Markers indicate means +/- SE. Brackets indicate statistically significant differences as a function of block found during *post hoc* testing. ANOVA found a significant effect of both block and feedback condition on box displacement and velocity. For box velocity, a significant interaction was found between block and feedback.

V. Discussion

A. *Vibrotactile feedback improves object manipulation*

Our results show a strong effect of the feedback paradigm, with the addition of vibrotactile feedback leading to increases in both box displacement and velocity. This result is at odds with the finding by Chatterjee et al. that pulse train frequency modulated vibrotactile feedback to perform a force-matching task did not result in a consistent overall reduction in error [14]. However, our results are consistent with our previous work that has shown that individuals can utilize amplitude modulated vibrotactile feedback to improve performance on an object manipulation task [13].

B. *Training improves performance using feedback*

There was a statistically significant effect of block on both box velocity and box displacement. Surprisingly, no significant increases were seen between block 3 and blocks 4 or 5. However, we found a significant interaction for box velocity between feedback modality and block. As seen in the lower panel of Fig. 2, the learning curve for visual + vibrotactile feedback is steeper than for vision alone. We predict that future experiments in a larger population will show a further significant improvement in performance during the use of the vibrotactile feedback.

C. *Summary*

We characterized the effect of visual and visual + force-based augmentative vibrotactile feedback modalities on an object manipulation task using a virtual myoelectric prosthesis. Using this functionally-relevant platform, we have found that the addition of vibrotactile feedback can aid object manipulation, and that training can further enhance these effects. These results are promising for future adoption of vibrotactile feedback for users of prosthetic hands.

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