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Relative to direct haptic feedback, remote vibrotactile feedback improves but slows object manipulation

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Abstract—**Most prosthetic hand users are limited to visual feedback of movement performance. To characterize the benefit of vibrotactile feedback for a task that lacks haptic feedback, a virtual environment was used to experimentally manipulate visual, task-relevant haptic, and remote vibrotactile feedback on simple object manipulation for unimpaired subjects. The combination of visual and remote vibrotactile feedback was compared to visual feedback alone, and to simultaneous visual and direct haptic feedback to represent ideal performance. Visual and vibrotactile feedback resulted in improvement of most performance variables including difficulty ratings relative to visual feedback alone. However addition of sensory cues to visual feedback increased trial times and the increase was steeper for vibrotactile than for haptic feedback. Specifically, during vibrotactile feedback the velocity did not change, but the duration of execution increased due to improved performance, resulting in increased trial times. This result suggests future exploration of performance improvement and execution speed for augmented sensory feedback.**

I. Introduction

The majority of myo-electric hand prostheses do not provide intentional proprioceptive or cutaneous feedback about movement performance. Instead, users must rely almost completely on visual feedback, which requires constant cognitive attention and can fail in degraded visual environments such as dim lighting. The addition of sensory feedback beyond vision to hand prostheses is a top design priority of users [1, 2], who also named "requires less visual attention to perform functions" as a top design request [3]. Multi-sensory feedback (such as visual and haptic) has been shown to mediate the self-attribution of body parts [4] in amputees, and to aid in object manipulation [e.g., 5, 6] in unimpaired individuals. While it is currently possible to provide contact force feedback on prosthetic hand and fingers during object manipulation [e.g., 7, 8], these technologies are not generally implemented in products.

Although implementation is impeded by cost and processing power, the most significant barrier is in the method of providing sensory information to users of prosthetic hands. A variety of approaches have been suggested [9-11]. One promising direction that has been previously explored is to provide force feedback by vibrotactile stimulation [8, 12]; the non-invasive nature of this approach would allow for immediate wide-scale implementation among users of prosthetic hands [9]. However, the relationships between object manipulation performance and speed as a function of feedback condition are still unclear. It has been suggested that direct haptic feedback provides physical constraints that could aid in task performance relative to force feedback provided via sensory substitution [13]. However, even with direct haptic feedback, only highly trained individuals improve performance without a significant increase in trial time [14].

Chatterjee et al. [12] presented 8 unimpaired individuals with vibrotactile stimulation on the upper arm during use of a myoelectric prosthesis simulator to complete an interactive force-matching task. Vibrotactile stimulation was based on the force sensed by a strain gauge at the carpal-metacarpal thumb joint. Use of this feedback did not result in a consistent overall reduction in force-matching error. Conversely, Pylatiuk et al. [8] presented 5 users of myoelectric prosthetic hands with vibrotactile stimulation of the prosthesis or skin of the residual limb during a simple object grasp task, finding decreases in contact forces. Here, vibrotactile stimulation was based on contact forces felt via a piezo-resistive force sensor on the palmar tip of the prosthesis. These studies resulted in conflicting performance results, and neither study task included task time as an outcome measure.

Systematic investigation of the effect and role of force feedback applied through vibrotactile stimulation relative to visual and direct haptic force feedback on object manipulation is needed to understand the optimum method for supplying force-based feedback to prosthetic users. This work describes the design of a robotic interface to study virtual object manipulation with which both visual and direct haptic feedback can be experimentally controlled, allowing comparison of augmentative methodologies for providing force feedback. Using this system, we compare user performance and rate with visual (V) and visual + remote (upper arm) vibrotactile (V+T) feedback, relative to the goal performance of visual + direct (on fingerpad) force-based haptic (V+H) feedback.

II. Methodology

A. Robotic Implementation of a Virtual Environment

The object manipulation task was to apply appropriate normal force to an object to allow for translation, and to drag it to a target without breaking it as quickly as possible. This

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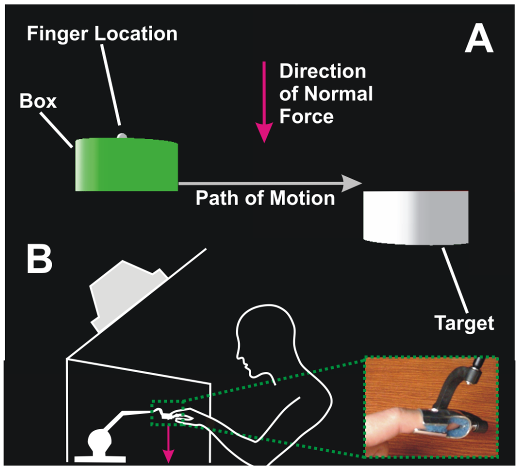

Fig. 1. A. Example screenshot of the visual feedback. B. Schematic of the Physical Set-up. Participants placed their right index finger into a custom splint attached to the end effector of the Phantom. The downward arrow shows the direction of the normal force on the virtual environment.

task was chosen due to the known difficulties of prosthetic hand users with appropriately applying normal force to delicate objects (e.g., picking up and manipulating a disposable plastic cup).

A Phantom Premium 1.0 robotic device (Sensable Technology) was used to monitor the three dimensional positions of the tip of the index finger, and to supply force-based haptic feedback when relevant. A projection system consisted of a frame above the Phantom, which supported an inverted video monitor, positioned at 45º toward the participant. A mirror was placed between the virtual environment and the monitor to permit reflection of images from the monitor (see Fig. 1, Panel B) to the user. Participants interacted with the virtual environment by placing their right index finger into a custom splint attached to the end effector of the Phantom.

The virtual environment was programmed in C++, with graphics driven by OpenGL, and consisted of one of three possible virtual objects (all cylinders oriented with the flat surface parallel to the ground plane, referred to as boxes) at the left end of the workspace (see Figure 1, Panel A). Three boxes with distinct stiffness characteristics were used. The stiffness characteristics of each box were defined as two continuous piecewise functions of vertical displacement. For displacements less than 1.7 cm, a linear stiffness (e.g., $F = kx$) was defined, and for displacements greater than 1.7 cm, the force-displacement was defined by a cubic polynomial (e.g., $F = k_1x^2 + k_2x + k_3$). Values of stiffness coefficients (k) were set to create scaled versions of the force-displacement relationship measured from a disposable plastic cup. The force required to overcome friction and translate the box was defined as 1.2 times the force at displacements of 1.7cm. After a sufficient normal force was applied to the box, the participant was able slide it to a target located 12.1 cm to the right. The force threshold to "break" each cylinder was defined empirically as 0.75N greater than the normal force required for movement, in order to make the task reasonably difficult to perform. The three boxes had varying levels of stiffness, with box 1 at the lowest stiffness and box 3 at the highest. Due to these differences in stiffness, the 0.75N window for moving the box resulted in differing allowable displacements of the finger during motion (0.9 – 2.7 mm), and thus differing difficulty for the 3 boxes.

The visual feedback used was a real time depiction of the location of the finger in the virtual environment (shown as a small sphere), and the position of the object (see Figure 1, Panel A). Deformations of the object were not shown, and visual feedback of finger location was occluded during penetration of the box.

B. *Experimental Protocol*

N = 8 unimpaired individuals participated in an initial experiment to determine the effects of visual and haptic feedback (conditions V and V+H). Participants were right-handed males, aged 19 – 28 (MEAN 22.8, STD 3.3). Over 1 hour, participants completed 120 trials of interaction with the virtual system (60 V, 60 V+H). Trials were presented in 10 blocks, randomized within block by box (1, 2, 3), feedback (V, V + H), and cognitive load (ON, OFF). An additional N = 8 unimpaired individuals participated in a second experiment to determine the effects of combined visual and remote vibrotactile feedback (condition V+T). These participants were right-handed individuals (4 females, 4 males), aged 19 – 27 (MEAN 21.4, STD 2.8). Over 1-1.5 hours, participants completed 60 trials of interaction with the virtual system. Here, trials were also presented in 10 blocks, randomized within block by box (1, 2, 3), and cognitive load (ON, OFF). In both experiments, participants were asked to slide a virtual box across the workspace to reach a target area as quickly as possible without breaking it.

During interaction, participants sat with their forearm resting on the front of the workspace, and their hand was free to move about the 3D workspace. Trials ended when the box reached the target or was broken. During V+H conditions, the force as defined by interaction with the virtual environment was applied to the finger via the Phantom. During V+T conditions, increases in force were translated to increases in amplitude of vibrotactile stimulation. Stimulation at 100 Hz was provided using a C2 tactor (Engineering Acoustics, Inc.) mounted to the lateral side of the upper arm, and secured with an elasticized cloth bandage.

The cognitive load consisted of an auditory 2-back test, in which participants listened to random digit strings during experimentation and were asked to respond verbally by identifying any numbers repeated with only one intervening number [15]. At the end of each trial, the participant was asked to report the difficulty of completing the motor task on an ordinal scale 1 – 5, in which 1 was very easy and 5 very difficult.

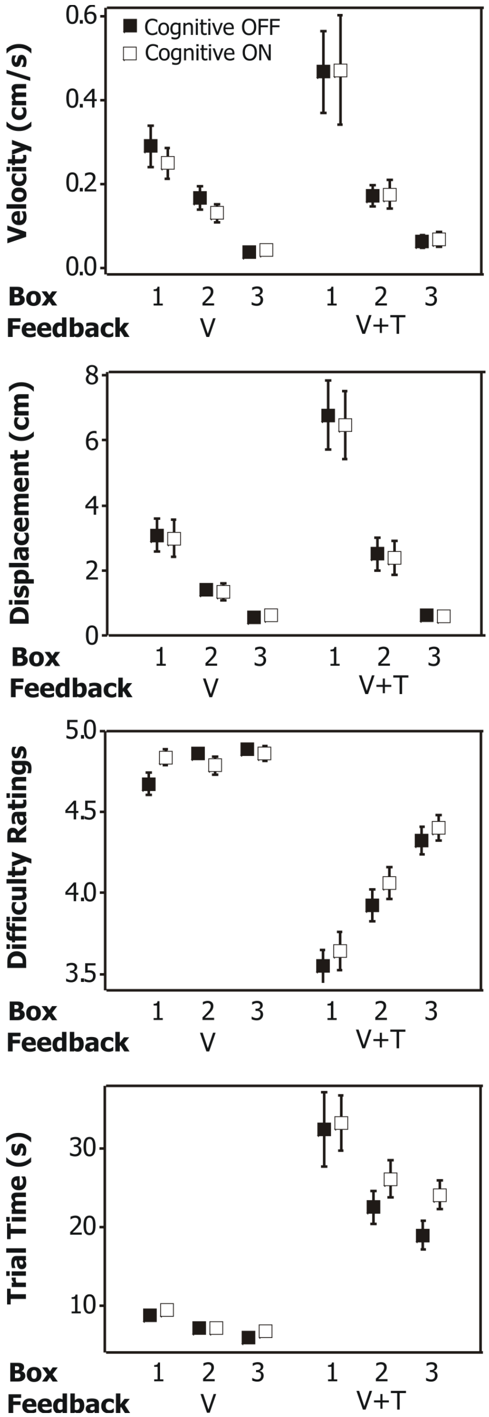

Fig. 2. Summary of the effects of box, feedback condition and cognitive task on experimental results. Markers show means +/- SE. (Velocity = Displacement / Trial Time).

Performance variables were box displacement (the distance toward the target that participants were able to translate the box during the trial), average box speed (box displacement normalized by trial length), and difficulty ratings. Data analysis was performed using custom software in MATLAB (Mathworks, Natick MA). Four factor general linear models in Minitab Statistical Software (Minitab Inc., State College, PA) were used to assess the effects ($p \leq 0.05$) of box, cognitive load, block, and feedback on the performance variables as well as task time, with *post hoc* two-sided Tukey's Simultaneous tests when appropriate to test the effects ($p \leq 0.05$) of cognitive load, box, and feedback condition.

III. Results

Results of statistical testing with general linear models indicated significant effects of box, block, and feedback condition on outcomes, and effects of cognitive task on average box velocity, trial time, and difficulty ratings. A summary of the noteworthy results are shown in Figure 2.

Box 1 (least stiffness) resulted in significantly greater displacements (MEAN = 10.5 cm, SE = 0.6 cm) than box 2 (medium stiffness; MEAN = 8.2 cm, SE = 0.5 cm) or 3 (highest stiffness; MEAN = 7.2, SE = 0.5 cm). Likewise, box 1 resulted in significantly higher average velocities (MEAN = 0.93 cm/s, SE = 0.06 cm/s) than box 2 (MEAN = 0.64 cm/s, SE = 0.05 cm/s) or 3 (MEAN = 0.48 cm/s, SE = 0.04 cm/s), and box 2 in significantly higher velocities than box 3. Trial times were significantly greater for box 1 (MEAN = 17.9 s, SE = 1.1 s) relative to box 3 (MEAN = 14.9, SE = 0.6 s). Difficulty ratings were significantly greater for box 3 (MEAN = 4.0, SE = 0.06) relative to boxes 1 (MEAN = 3.6, SE = 0.06) and 2 (MEAN = 3.8, SE = 0.06), and for box 2 relative to 1.

Significantly greater displacements were seen during V+T (MEAN = 3.2 cm, SE = 0.3 cm) and V+H (MEAN = 21.0, SE = 0.5 cm) relative to V (MEAN = 1.7 cm, SE = 0.1 cm), and greater displacement during V+H than V+T. Conversely, although V+H showed significantly greater velocities (MEAN = 1.66 cm/s, SE = 0.06 cm/s) than V (MEAN = 0.15 cm/s, SE = 0.01 cm/s) and V+T (MEAN = 0.24 cm/s, SE = 0.3 cm/s), V+T did not show increased velocities relative to V. Significantly increased trial times were found during V+T (MEAN = 26.2 s, SE = 1.2 s) relative to V (MEAN = 7.5 s, SE = 0.2 s) and V+H (MEAN = 14.6 s, SE = 0.4 s), and during V+H relative to V. Difficulty ratings were lowered during V+T (MEAN = 4.0, SE = 0.04) and V+H (MEAN = 2.6, SE = .06) relative to V (MEAN = 4.8, SE = 0.02), and during V+H relative to V+T.

Cognitive task resulted in lowered velocities (MEAN = 0.64 cm/s, SE = 0.04 cm/s, relative to MEAN = 0.73 cm/s, 0.04 cm/s) increased trial times (MEAN = 17.0 s, SE = 0.6 s, relative to MEAN = 15.2 s, 0.7 s), and increased difficulty ratings (MEAN = 3.8, SE = 0.05, relative to MEAN = 3.7, 0.05).

A trend of increased displacement, velocity, and trial time, and decreased difficulty was seen as a function of block.

IV. Discussion

A. Effects of remote vibrotactile feedback on performance

The addition of visual + remote vibrotactile (V+T) feedback resulted in increased box displacement and decreased difficulty ratings relative to V alone, and decreased displacements and increased difficulty ratings relative to visual + direct haptic (V+H) feedback. Although V+T resulted in decreased box velocity than V+H, no difference in box velocity was found between V and V+T.

The improvement seen in performance variables with V+T relative to V in the current work matches the results of [8], who found that force-based vibrotactile stimulation allowed users to reduce contact forces during a simple object grasp task. It does not match well with [12], who did not find consistent overall reduction in error using force-based vibrotactile feedback to perform a force-matching task. The location of vibrotactile stimulation here is similar to the locations used in the previous studies of Chatterjee et al. [12] and Pylatiuk et al. [8]. However, the stimulation paradigms used in those two studies differed from one another, and from the approach in the current work. Without further research, it is unclear whether the current results are more consistent with [8] because of the motor task employed, or because of the stimulation paradigm. Future testing with this system will examine a variety of stimulation paradigms.

B. Effects of remote vibrotactile feedback on task time

Despite the gains in performance variables of box displacement and difficulty ratings during visual + remote vibrotactile feedback relative to visual alone, no gains were seen in average box velocity during V+T relative to V. This is likely a result of the increased trial times during V+T relative to both V and V+H conditions. In fact, mean trial times during V+T were nearly twice those during V+H.

Overall, although individuals using V+T were able to translate the box further and with more ease than those using V alone, they did so at the cost of exceptionally lengthy trial times. Participants were instructed to translate the box to the target as quickly as possible without breaking it, but were not given any specific instruction about the relative importance of speed versus box preservation. Results may differ if subjects are given alternative task criteria, such as the instruction to prioritize speed at the cost of breaking the box.

C. Effects of cognitive load

Despite the fact that cognitive load resulted in significantly decreased velocities, increased trial times, and increased difficulty ratings, there was no effect seen on box displacement. Therefore, although performance of a simultaneous cognitive task did not impede participants' ability to translate the box, it caused them to perform the motor task more slowly and to associate the task with increased difficulty. However, as can be seen visually in Figure 2, these effects were less marked than those associated with the addition of vibrotactile to visual feedback. It is possible that the cognitive task employed is too unnatural to cause the significant delays seen with the addition of the vibrotactile signal, a "task" that is meaningful for task completion and during which attention may aid in task performance.

D. Summary and Future Directions

We have characterized the effect of visual and haptic feedback modalities on an object manipulation task, both with and without a cognitive load. In addition, the effects of the addition of augmentative force-based vibrotactile stimulation to visual feedback were characterized relative to visual and haptic feedback. Using the functionally-relevant platform described here, our future work will test and compare other approaches for augmented sensory feedback.

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