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Effect of Vibrotactile Feedback on Robotic Object Manipulation

Qi An, Hajime Asama, Yoky Matsuoka, and Cara E. Stepp

Abstract— **Recently there have been increased demands to improve function of prosthetic hands. One of the directions is implementation of force feedback to improve object manipulation. Previously we have employed vibrotactile stimulation to safely and non-invasively provide force feedback, showing that participants could improve task performance in a virtual environment. This work used robotic devices to develop a physical experimental environment to replace the previous virtual experimental conditions and to test the efficacy of vibrotactile feedback. Unimpaired participants (N=6) were asked to drag a box to a target location. Performance of users was measured based on total box displacement, average box velocity, their subjective difficulty ratings, exerted power, and average applied normal force on the box. With vibrotactile feedback, participants were able to statistically significantly improve their task performance as measured by all parameters except average velocity. This result strongly supports the use of vibrotactile feedback as a simple methodology to provide force feedback to prosthetic hand users.**

I. Introduction

Recently many hand prostheses have been developed, but most of them cannot fully contribute to improvement of prosthesis users' Activities of Daily Living [1]. In order to improve the situation, there are suggested enhancements for hand prostheses, such as weight reduction, lower cost, fine control of fingers, or implementation of sensory feedback. Many recent studies have focused on implementation of fine control to prostheses, and many control strategies of myoelectric hands have been developed [2] [3]. However, the function to provide sensory feedback to users has not been widely implemented in commercial products.

In fact, it has been shown that sensory feedback improves user ownership of prosthetic hands [4]. When typical individuals manipulate an object, they dexterously perceive and utilize many types of sensory information from their fingers, such as temperature, vibration or pressure. Therefore matching sensory information to their intentional actions is useful for natural usage of prostheses hand. Hence, many of prosthesis users have to rely mainly on their vision for object manipulation. This current situation requires prostheses users to use constant concentration. Therefore, it has been suggested to implement sensory feedback to prosthetic hands [5] in order to alleviate the visual attention and improve functions of hand prostheses. Recent sensor technology has enabled development of prosthetic hands with embedded sensors to measure pressure information on prosthetic fingers [6]. We have focused on providing applied force information, which is essential for object manipulation.

There are several ways to provide sensory feedback to prostheses hand, and it has been reported that some prosthetic hand users can successfully use those technologies. For example, Kuiken et al. have showed that invasive reinnervation surgery, which gives feedback to their chest, could enhance function of a prosthetic hand [7]. However, this methodology requires medical surgery and therefore it cannot yet be used widely. Another study demonstrated that electrocutaneous stimulation could be used for feedback information about both force and posture of prosthetic fingers [8]. Participants in this study could identify force and posture, but the ratio of correctly identified answers was low. Among those kinds of both invasive and noninvasive methodologies to provide sensory feedback [9] [10], vibrotactile stimulation seems to be a safe and easy approach.

Our previous research developed an experimental system that used an interactive robotic device to test users' object manipulation ability with vibrotactile feedback in a virtual space [11]. In the study, four different stimulation sites (finger, arm, neck, and foot) were tested for eighteen unimpaired individuals. We showed that object manipulation performance improved with the use of vibrotactile feedback regardless of their stimulation sites. In our recent longitudinal study, participants showed continuous improvement of object manipulation performance through seven days training [12]. These studies strongly support the possibilities of vibrotactile feedback, but participants performed a virtual task throughout these previous experiments [11] [12] [13]. Therefore, in this study, we have replaced the virtual experimental environment with a physical environment to assess the effects of vibrotactile feedback. In this paper, our objective is to test whether individuals can utilize vibrotactile feedback and improve their performance to manipulate a physical object.

II. Methods

A. Experiment Overview

In this study, an object manipulation system using two robotic devices was developed to test the effect of vibrotactile feedback. Participants (N=6) were asked to control a robotic device with their index finger to apply normal force to a box and drag it to a target position without breaking it. In order to test how vibrotactile feedback affects performance, the experiment consisted of 40 trials with different conditions, such as different types of boxes, whether participants had vibrotactile

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An, Q. and Asama, H. are with Faculty of Precision Engineering, Department of Engineering, University of Tokyo, Tokyo, Japan (e-mail: anqi@robot.t.u-tokyo.ac.jp)

Matsuoka, Y. is with Department of Computer Science and Engineering, University of Washington, Seattle, USA

Stepp, C.E. is with Speech, Language, and Hearing Sciences, Department of Biomedical Engineering, Boston University, Boston, USA

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feedback, or whether they performed a simultaneous cognitive test. Manipulation performance was evaluated in terms of total box displacement, average box velocity, subjective difficulty ratings of the task by participants, exerted power to move the box, and average applied normal force on the box.

B. Experimental Setup

Two PHANToM Premium 1.0 robotic devices (Sensable Technologies, Inc., Woburn, MA) were used in our experiment (PHANToM1 and PHANToM2). PHANToM1 was coupled with the index finger of participants whereas PHANToM2 manipulated the box (Fig. 1-(A)). The index finger of the participants was coupled with a custom-made finger cuff, and the participants could move their index finger freely.

The movement of these two devices, PHANToM1 and PHANToM2, were synchronized with proportional control; PHANToM2 ($\boldsymbol{P}^2 = (p_x^2, p_y^2, p_z^2)$) moved according to the position of PHANToM1 ($\boldsymbol{P}^1 = (p_x^1, p_y^1, p_z^1)$). In order to enforce movement of PHANToM2 to that of PHANToM1, force was generated on an end point of PHANToM2 ($\boldsymbol{F} = (F_x, F_y, F_z)$). The force was determined based on positions of the two PHANToMs. Initial positions of both PHANToMs ($\boldsymbol{P}_{init}^{1,2}$) were recorded, and difference between current positions and initial positions were calculated as $\boldsymbol{P}_{diff}^{1,2} = \boldsymbol{P}^{1,2} - \boldsymbol{P}_{init}^{1,2}$. From these difference of positions, $\boldsymbol{F}$ was computed based on (1). In the equation, a is a constant proportional gain to adjust movements of two devices.

$$\boldsymbol{F} = a(\boldsymbol{P}_{diff}^1 - \boldsymbol{P}_{diff}^2) \tag{1}$$

Figure 2 shows an example movement of both PHANToMs in a trial. Red solid lines show the position of PHANToM1 while blue dotted lines indicate that of PHANToM2. The top panel in Fig. 2 indicates movement in a x direction. On the other hand, the middle and bottom panels of Fig. 2 show movement in y and z directions, which indicate that the positions of two PHANToMs were successfully synchronized in those directions. Before PHANToM2 touches the box, PHANToM2 follows the movement of PHANToM1, but the difference of positions of the two devices gets larger when PHANToM2 touches the box. When the index finger of a participant gets lower than the top surface of the box, PHANToM2 starts pushing the box. The normal force is generated from the height difference of both PHANToMs, thus participants need to move their index finger deeper than the height of PHANToM2 to apply a normal force.

A board with a ruler was placed beneath the box in order to measure total box displacement in the experiment. The box was placed at the same start point after each trial. During the entire experiment, participants wore noise cancelling headphones (Bose, Framingham, MA), which were used to play a cognitive test (described in the next section) as well as low-level masking noise to prevent noise from vibrotactile stimulation from being used as auditory feedback.

During the experiment, participants received vibrotactile feedback through a C2 tactor (Engineering Acoustics, Inc.)

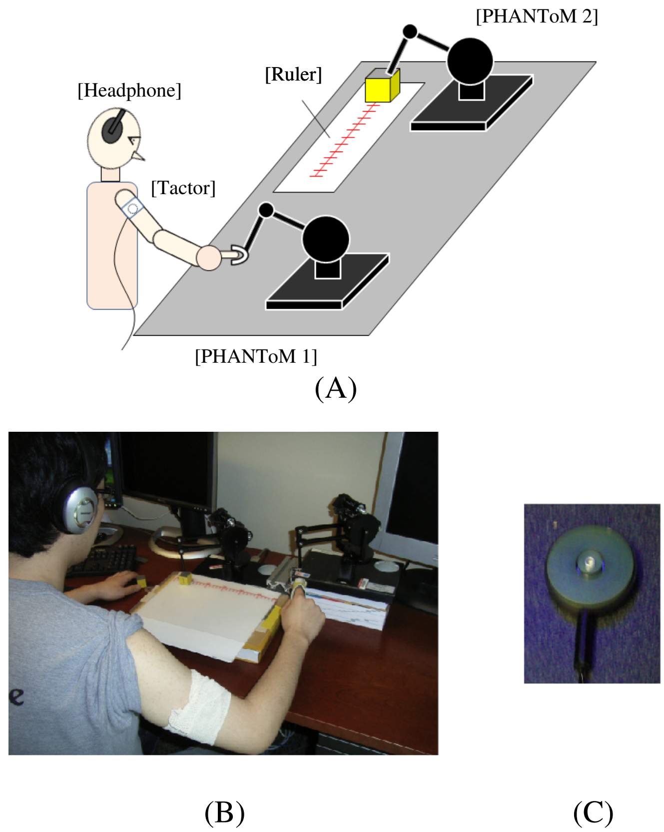

Fig. 1. (A) Schematic of our experimental system. (B) Photograph of the experimental set-up. (C) C2 tactor.

as in Fig. 1-(C), and they did not receive any feedback (tactile or force feedback) to their index finger coupled with PHANToM1. Our previous study [11] showed no statistical significance between vibrotactile stimulation sites. Therefore, in this study we chose the right upper arm for the location to attach the tactor with an elasticized cloth bandage (Fig. 1-B). The amplitude of the vibration was changed linearly based on the exerted force on PHANToM2 ($|\boldsymbol{F}|$); the more force participants applied, the more amplitude of vibrotactile stimulation they could feel on their skin. The vibrotactile stimulation rate was at 250 Hz, at which glabrous skin is maximally sensitive [14] [15].

C. Task

1) Experimental Task: For our experimental task, the same type of object manipulation, a box dragging task, was chosen as in our previous study [11] [12]. In the current study, we replaced the previous virtual task space with a physical experimental environment.

Participants were asked to control PHANToM1 to apply appropriate normal force to the box to allow for translation, and to drag it to a target as quickly as possible without breaking it. The position of this robotic device was synchronized to the position of the index finger of participants with proportional control as described in the previous section.

Figure 3 depicts the task employed in our experiment.

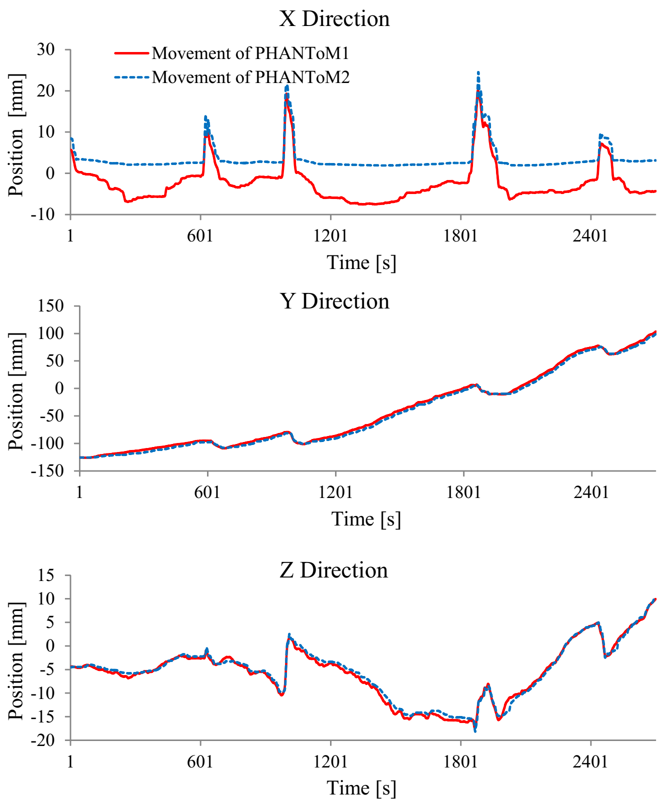

Fig. 2. Above graphs indicate movement of two PHANToMs in the x, y, and z directions respectively.

Participants were asked to push on the box vertically in order to drag it to the target position 25 cm to the right of the initial position. In the experiment, there was a virtual threshold for boxes to be broken in order to make this experimental task comparable to our previous studies. Therefore, if the normal force exerted on the box exceeded the threshold, the box was assumed to be broken and a trial would finish.

2) Evaluation: Performance of participants for each trial was measured in terms of total box displacement [cm] in the y direction, average box velocity [cm/s], difficulty ratings, exerted power to move the box [W], and average applied normal force exerted on the box in a x direction [N/s]. Total

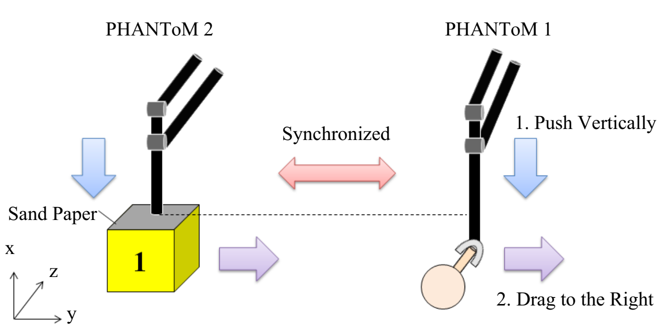

Fig. 3. Participants were asked to push the box on the top surface vertically and drag it to a target position located 25 cm to the right of the start position.

box displacement in the y direction (y-axis in Fig. 3) was measured manually with the ruler of the board after each trial. Any displacement in the z direction was not considered. Average box velocity was obtained as dividing the total displacement by the total trial time. This total trial time was obtained from a log file of each trial recorded by the computer. The log file stopped recording when the normal force applied to the box exceeded the threshold, or it was manually stopped when the box reached the target position. Difficulty ratings were a subjective evaluation of each task, asking how hard participants felt about the trial was. These were obtained by recording the participant's verbal response.

Exerted power of the robotic device to move the box was calculated as in (2). It indicates how efficiently participants could move the box toward the target place in the physical environment. In the equation, D_{total} is total box displacement, F_y is force applied to the box in the y direction when PHANToM2 touches the box. T_{total} is the total time while PHANToM2 is dragging the box. This force is decided when the difference of positions of two PHANToMs in the x direction exceeds 0.5 cm, assuming that PHANToM2 is touching the top surface of the box.

$$Power = \frac{D_{total} \sum_{t=0}^{t=T_{total}} F_y(t)}{T_{total}} \tag{2}$$

Average applied normal force is calculated from dividing the total applied normal force ($F_x(t)$) by time, T_{total}, while PHANToM2 touches the box (eq.3). This measurement represents how hard participants pushed the box. The larger the average applied normal force is, the more unnecessary force participants exerted on the box. This force is also decided when the difference of the positions of PHANToM1 (p_x^1) and PHANToM2 (p_x^2) exceeds 0.5 cm.

$$AverageAppliedForce = \frac{\sum_{t=0}^{t=T_{total}} F_x(t)}{T_{total}} \tag{3}$$

3) Cognitive Task: During half of the trials, participants were asked to perform a simultaneous cognitive test during the manipulation task. The task was an auditory 2-back test [16]. Participants listened to a finite 16-digit string of numbers (each digit was 1–9), and they were asked to identify verbally all numbers repeated with one intervening number. Before starting the experiment, all participants practiced 24 sets of cognitive test to get used to it.

The aim of this test was to test if users could utilize vibrotactile feedback in the face of the simultaneous cognitive load. In a daily life, individuals are sometimes required to perform two different actions, such as an object manipulation while chatting to others. In order to fully implement this feedback methodology into a prosthetic hand, vibrotactile stimulation should be helpful under the simultaneous cognitive load. Therefore object manipulation performance was evaluated with the cognitive test.

4) Box Properties: There were two different cubed boxes employed in our study (box1 and box2). These boxes had the same dimensions (2.54 cm per side), but different densities;

the weights for box1 and box2 were 0.0885 kg and 0.4985 kg respectively. Numbers (1 and 2) were written on the anterior face to indicate the type of box to the participant.

Friction of the two boxes was made to be the same by covering them with the same packing tape. Additionally a piece of sandpaper was attached to a top face of each box above the packing tape in order to increase the friction between PHANToM2 and the boxes. The sandpaper was replaced between each trial to avoid changes of friction due to the sandpaper becoming worn out.

The box could be moved only when the normal force (F_x) exceeded the thresholds of the boxes to start moving (F^1_{move} and F^2_{move} for box1 and box2 respectively). This threshold was obtained from a preliminary experiment: F^1_{move} was 0.7 N and F^2_{move} was 1.7 N. Thresholds for "breaking the box" (F^1_{break} and F^2_{break}) were arbitrarily decided as $F^{1,2}_{break} = F^{1,2}_{move} + 0.5$N, consistent with our previous studies [12].

D. Experimental Protocol

All participants performed 40 trials of the box dragging task. The experiment consisted of 5 sets of eight trials randomized by three different conditions: box type (box1 or box2), whether participants had a cognitive test or not, and whether they had vibrotactile feedback or not. These eight types of trials were pseudorandomly distributed in one set, and every set had all eight types of trials.

During the experiment, participants sat in a chair and it was ensured that participants could move their right hand and index finger freely. Also, after every trial they were asked to specify difficulty ratings between 1–5 where 1 was the easiest and 5 was the most difficult. The duration of the experiment was about 40-50 mins including cognitive test practice.

E. Participants

In total, 6 male individuals participated in our experiment (average age = 22.0 years, STD = 2.0 years). All participants were right-handed with no known problems with their hand. Consent was obtained from all of them before the experiment started in compliance with the Institutional Review Board of the University of Washington.

F. Data Analysis

Performance of each participant was evaluated on the following five outcomes: total box displacement, average box velocity, difficulty ratings, exerted power to move the box, and average applied normal force.

A three factor repeated measures analysis of variance (ANOVA) was performed to assess the effects of vibrotactile feedback (on or off), box type (box1 or box2), cognitive task (on or off), with post hoc two-sided Tukey's tests when appropriate. In order to evaluate statistical significance, significance level was set to $p < 0.05$ for all analyses.

III. Results

Table 1 shows five performance outcome measures. In the table, "Dist" stands for total box displacement, "Velo" represents average box velocity, "Diff Rate" indicates difficulty ratings, "Power" represents exerted power, and "Ave Force" shows average applied normal force.

Results of statistical analysis indicate significant effects of vibrotactile feedback on total box displacement (DF=1, F=7.33, p=0.0073), difficulty ratings (DF=1, F=8.1, p=0.0048), exerted power (DF=1, F=4.21, p=0.041), average applied normal force (DF=1, F=5.92, p=0.0157), but did not show significant effect on average box velocity (DF=1, F=1.44, p=0.231). A significant effect of the cognitive test was seen only in difficulty ratings (DF=1, F=16.3, p=0.0001) whereas the test had few effects on total box displacement (DF=1, F=0.13, p=0.71), average box velocity (DF=1, F=0.47, p=0.49), exerted power (DF=1, F=0.08, p=0.77), or average applied normal force (DF=1, F=0.01, p=0.92). Box types had significant effects on all outcomes: total box displacement (DF=1, F=7.07, p=0.0084), average box velocity (DF=1, F=31.21, p <0.000), difficulty ratings (DF=1, F=34.7, p <0.001), exerted power (DF=1, F=26.24, p <0.001), average applied normal force (DF=1, F=1079.36, p <0.001).

TABLE I

MEAN AND STANDARD ERROR OF OUTCOME MEASURES

	Feedback		Cognitive Test		Box	
	OFF	ON	OFF	ON	1	2
Dist [cm]	17.6	20.5	18.9	19.2	20.4	17.7
SE	0.8	0.7	0.8	0.8	0.7	0.8
Velo [cm/s]	0.87	0.75	0.84	0.77	1.09	0.52
SE	0.10	0.05	0.09	0.07	0.10	0.04
Diff Rate	3.01	2.65	2.58	3.08	2.46	3.20
SE	0.11	0.11	0.11	0.10	0.10	0.11
Power [W]	0.107	0.122	0.113	0.116	0.096	0.133
SE	0.006	0.005	0.006	0.006	0.003	0.007
Ave Force [N/s]	1.03	0.994	1.01	1.01	0.771	1.25
SE	0.024	0.025	0.009	0.013	0.025	0.023

Tukey tests indicated that compared to box1, box2 resulted in a significant decrease in average total displacement from 20.4 cm (SE=0.7 cm) to 17.7 cm (SE=0.8 cm; 13.6% decrease), a significant decrease in average velocity from 1.09 cm/s (SE=0.10 cm/s) to 0.52 cm/s (SE=0.04 cm/s; 52.3% decrease), a significant increase in difficulty ratings from 2.46 (SE=0.11) to 3.20 (SE=0.11; 30.2% increase), a significant increase in exerted power from 0.096 W (SE=0.003) to 0.133 W (SE=0.007; 39.0% increase), and significant increase in average force from 0.771 N/s (SE=0.009 N/s) to 1.251 N/s (SE=0.013 N/s; 62.2% increase).

Trials with a cognitive test showed a significant increase in difficulty ratings from 2.6 (SE=0.1) to 3.1 (SE=0.1; 19.7% increase).

Figure 4 shows means of the five outcome measures (distance, velocity, difficulty ratings, exerted power, and average applied normal force) as a function of vibrotactile feedback (on or off). Trials with vibrotactile feedback showed a statistically significant increase in average total displacement from 17.6 cm (SE=0.8 cm) to 20.5 cm (SE=0.7 cm; 16.0% increase), a significant decrease in difficulty ratings from 3.01 (SE=0.11) to 2.65 (SE=0.11; 11.9% decrease), a significant increase in exerted power from 0.107 W (SE=0.006 W) to 0.112 W (SE=0.005 W; 14.0% increase), and a significant decrease in average applied normal force from 1.029 N/s (SE=0.024 N/s) to 0.994 N/s (SE=0.025 N/s; 3.5% decrease). With vibrotactile feedback, average box velocity was not increased statistically significantly.

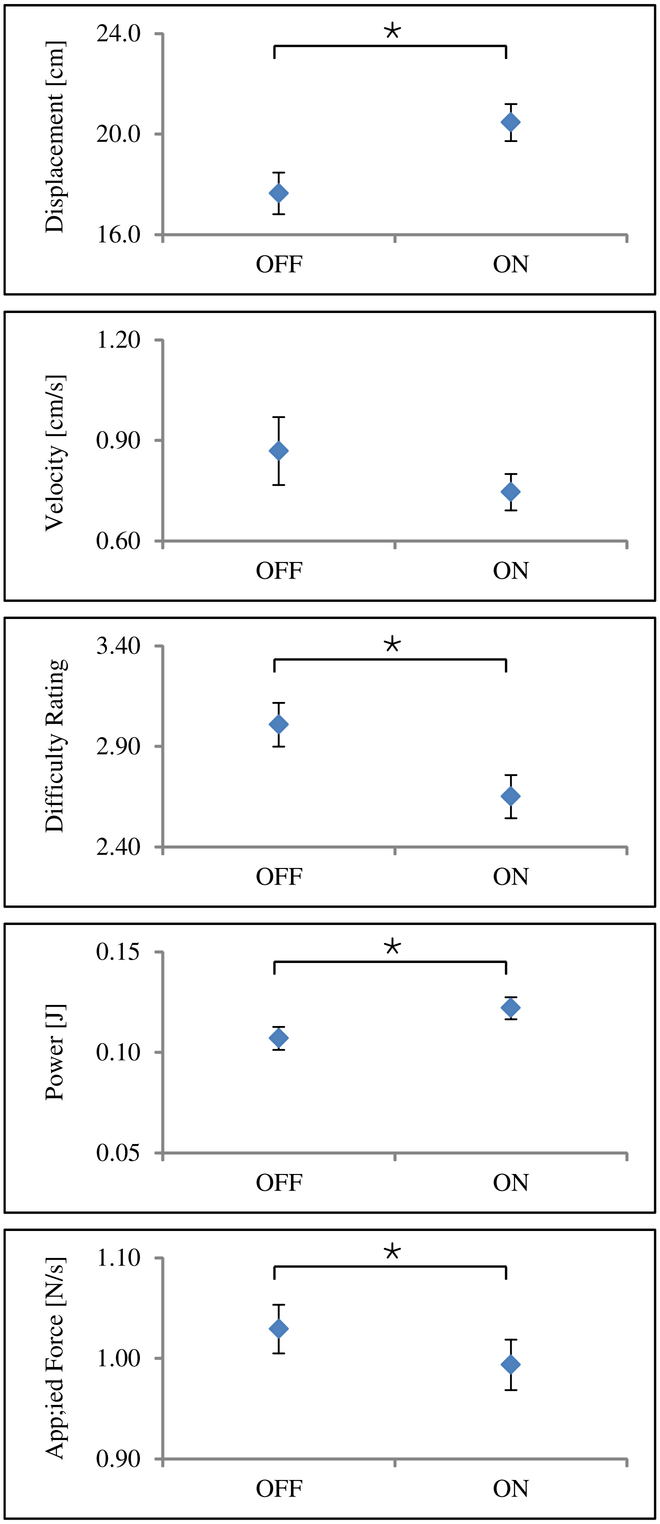

Fig. 4. Mean performance outcomes as a function of vibrotactile feedback (on or off). Error bars indicate +/- SE.

IV. Discussion

We found that participants could improve their performance outcomes with vibrotactile feedback. In particular, use of vibrotactile feedback resulted in statistically significant changes in total box displacement (16.0% increase), subjective difficulty ratings (11.9% decrease), exerted power (14.0% increase), and average applied normal force on the box (3.5% decrease). Average box velocity decreased from 0.87 cm/s (SE=0.1 cm/s) to 0.75 cm/s (SE=0.05 cm/s), but not statistically significantly. These results are similar to the results from our previous study that employed a virtual task environment [11].

In the previous experiment, participants operated a similar experimental task; they were asked to drag a box with their index finger in a virtual environment. The results of our previous study [13] showed that trials with vibrotactile feedback significantly increased in displacement from 1.7 cm (SE=0.1 cm) to 3.2 cm (SE=0.3 cm ; 88.0% increase), significantly increased in trial times from 7.5 s (SE=0.2 s) to 26.2 s (SE=1.2 s; 249.3% increase), velocity from 0.15 cm/s (SE=0.06 cm/s) to 0.24 cm/s (SE=0.3 cm/s; 60.0% increase) but not significantly, and significantly decreased in difficulty ratings from 4.8 (SE=0.02) to 4.0 (SE=0.04l 16.7% decrease). In this experiment, average box velocity was also not significantly increased.

Both experiments show performance improvement in total box displacement and difficulty ratings with vibrotactile feedback, but without a significant effect on average box velocity. While the improvement in difficulty ratings is similar between virtual and physical environments, the improvement of total box displacement in the current study (16.0% increase) is rather smaller than that found in the previous virtual environment (88.0% increase). One reason for this difference might be that in this experiment, the participants could actually see the object and their finger, and therefore they were able to move the box further without vibrotactile feedback. In our previous experiment, participants could not see their finger position while dragging a box and they may have relied more on the vibrotactile feedback compared to the current experimental setup.

The average box velocity was not increased significantly with vibrotactile feedback in both experiments. Our results show that with vibrotactile feedback people could move the box further, but that they needed to spend more time to perform the trials. Although this seems like a negative aspect of using vibrotactile feedback, our previous longitudinal study [12] showed that average box velocity was increased about 280% over seven days of training. Thus, this slower manipulation speed can be easily overcome with multi-day training.

Our results show that vibrotactile feedback has a positive effect on the exerted power and the average applied normal force. An increase in exerted power indicates that participants could move the box effectively, and a decrease in the average applied normal force shows they did not need to exert unnecessary force with vibrotactile feedback. In addition to this, participants rated that the task got easier with vibrotactile feedback. These results would strongly support usage of vibrotactile feedback to improve prosthesis functions.

A simultaneous cognitive test had a small effect on our experiment. Although our previous study showed an effect of the cognitive task for all outcomes [12], here only subject difficulty ratings were increased by the cognitive task, while the rest of the outcomes were not significantly changed. This is likely a result of the longer trial time; the average trial time was 34.9 s (SE=1.85) in the current study compared to 16.1 s in the previous study [13], whereas the cognitive task lasted only 16.0 s. Participants were asked to manipulate the box at the same time as the cognitive test, but after the cognitive test was finished, they could continue to manipulate the box without the test. Therefore in this study, the effect of the cognitive test seems to be relatively less than the previous experiment. In our future experiments, a longer cognitive test will be used.

The factor of box type had a significant effect on all outcomes. Participants could move the lighter box further, faster, and more effectively. They felt that moving the heavier box was more difficult and average force applied on the box was increased relative to the lighter box.

A linear mapping of force to vibrotactile stimulation amplitude was employed in this paper, but another type of mapping might show better performance. In future studies, different types of feedback mapping need to be tested. For instance, a logarithmic or exponential mappings could be more effective.

Another future direction of this research is a test of a multi-dimensional feedback system. This paper focuses on feedback from a single point; however, in order to fully enhance the functions of prosthetic hands, it is necessary to test whether people can simultaneously associate feedback from all five fingers.

In addition, the location of remote feedback also needs to be considered, especially in the case of a multi-dimensional feedback system. In our study, participants were able to improve their performance with vibrotactile feedback located on their right upper arm, but it may be harder for them to get used to different feedback if stimulated body places are close each other. Therefore examination of several different combinations of body places to be provided feedback is worth consideration.

Finally, it would be interesting to test other movement-related information in addition to exerted force. In our study, only force information was given to users and posture of finger was not considered, but posture information may also help to improve function of prosthetic hands. Thus, our future work will test feedback of both force and posture information with a functional task.

V. Conclusion

In conclusion, participants were able to utilize remotely applied vibrotactile feedback to improve their object manipulation performance in a physical robotic environment. Total box displacement, difficulty ratings, exerted power, and average applied normal force were significantly improved with vibrotactile feedback. This indicates that with vibrotactile feedback participants could move boxes further, they felt the task was easier, and they could move boxes more efficiently.

VI. Acknowledgments

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