Tactile Feedback of Object Slip Improves Performance in a Grasp and Hold Task

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ABSTRACT

Electronically controlled prosthetic devices offer more functionality than traditional prostheses, but the lack of haptic feedback makes everyday tasks difficult to perform. This research effort explores the effectiveness of vibratory tactile feedback of slip information for improving performance in object manipulation, specifically for grasping and lifting objects without slipping. A user interacts with a virtual environment via a SensAble Phantom. Force feedback simulates contact with objects, and tactile feedback alerts the user when an object is slipping from grasp. Analysis of the results showed that tactile feedback considerably improved performance when visual feedback was not provided. When participants were not able to see the virtual object slipping, they were able to rely on the vibrating feedback and were alerted about the object slipping. With this information, they were able to recover the virtual object from slips much more frequently than with force feedback alone. These results can be applied to advancements in prosthetic hands, which may include improving dexterity and performance of everyday tasks like drinking a glass of water.

Index Terms: H.1.2 [Models and Principles]: User/Machine Systems—Human Information Processing; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

Traditional upper limb prosthetic devices lack the touch feedback that is necessary for dexterous manipulation of objects. In an intact upper limb, an individual's nerves can identify object weight or detect an object slipping from grasp and direct that information to the central nervous system via afferent nerve pathways. The person can then adjust the grasp by sending their intent to the neuromuscular system. In this way, objects can be handled without being dropped or broken. In contrast to an able-bodied person, an upper extremity amputee has no afferent or efferent pathways past the farthest point of the residual limb for this transfer of information and intentions.

To address this issue, research in prosthesis control has seen considerable innovation in recent years. Myoelectric sensors allow user intent to control movement of the prosthetic limb without mechanical couplings to intact joints. However, the lack of a direct physical connection means no touch feedback from the prosthetic gripper. Users rely heavily on vision to control the endpoint of the prosthetic arm and would prefer to be able to control their limbs with less visual attention [1]. Having to watch a prosthetic gripper carefully is mentally taxing and much less efficient than using the touch feedback that intact limbs provide. Levels of mental workload in human-machine interaction can be quantified through brain imaging techniques (e.g., [2, 3]) and questionnaires, and it has been shown that purely visual control of a prosthesis requires more mental effort than control with additional feedback cues [12].

In an effort to improve prosthesis feedback systems and recreate natural touch sensations for amputees, techniques have been developed to electrically stimulate afferent nerves within the residual limb [18], but surgical risks and signal degradation make this method non-ideal. Non-invasive alternatives include sensory substitution via force, tactile, and skin stretch actuators (e.g., [4, 9, 14]). Some of these methods have been shown to aid in grasping with prosthetic hands; for example, vibrotactile feedback and force feedback have been used to display grip force [6, 7, 10].

A grasp and lift task is an appealing choice to investigate touch feedback in dextrous manipulation because it involves coordinating grip force and load force with object weight [13]. It is a planned movement and requires an internal model of the object's properties. Healthy individuals can use touch sensations to garner this representation, but upper limb amputees rely primarily on vision. Brown et al. studied the value of including force and tactile cues in a grasp and lift task with a prosthetic device. In their experiment, an object slipped from the participant's grasp significantly fewer times when the force of the gripper was relayed to the user with either a torque about the elbow or a vibrational feedback cue [6].

In addition to force information, a person uses cutaneous sensations from fingertips when holding an object to detect the onset of slip, to gain information about object friction, and to update an internal representation of the object. These sensations have been found to be more valuable to performance than vision for tuning motor output to the object properties [13]. Individuals completing a grasp and lift task without fingertip sensory feedback to collect slip information grip an object with a higher than necessary force before lifting it, often breaking the object [16].

Because of the importance of slip feedback to able-bodied individuals in grasp and lift tasks, we hypothesize that providing slip feedback to amputees in addition to force feedback will improve their grasping performance over providing force feedback alone. Some slip feedback systems have been previously developed for grasping in prosthetic hands [11], but these systems have not yet been tested in practical applications. Promising results for the use of slip feedback have been shown in a laparoscopic surgical grasping task [21], but the system used in this study is not practical for prosthetic applications. Slip detection on robotic fingertips has been explored to automate grip within prosthetic devices, but it is not relayed to the user [15].

We explore the efficacy of a slip feedback system that would be practical for prosthesis use through a human subject study in which healthy individuals interacted with a virtual environment. This study investigates the use of tactile feedback via vibrating tactors on the upper arm to impart information about object slipping. Vibrotactile feedback was chosen to convey slip information because in previous studies it was shown to be valuable for conveying other types of haptic information like force and proprioception [6, 8, 20, 23]. Previous studies have explored vibration and slip in other ways. Okamoto et al. found that, in a human grasping test, sending a vibratory cue before inducing object slip improved force adjustment [17]. Slip sensations detected on the outside surface of a glove and replicated via vibrations to the user's fingertips inside

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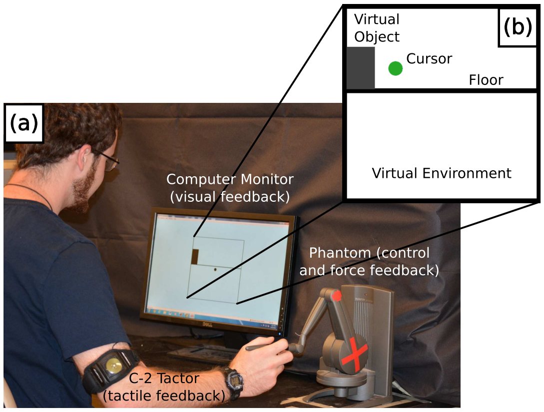

Figure 1: (a) A user seated at the experimental set-up. The virtual environment is displayed on a computer screen, and the user interacts with the environment using the Phantom. Force feedback is provided via the Phantom, and slip feedback is provided via the C2 tactor on the arm. (b) The initial setup of the virtual environment. The green cursor is controlled by the participant. The floor halfway up the room falls after three seconds, and the participant must press the cursor against the object to keep it from falling as well.

the glove were shown to improve grip adjustments as well [19].

Instead, this investigation substitutes slip vibrations that would naturally be felt by the fingertips onto the upper arm, where transradial amputees could sense them. This study centers on the grasp and lift task, mirroring the study by Brown et al. [6]. The task was recreated in a virtual environment. Force feedback was provided that correlated to gripping force, and vibrational cues on the user's upper arm signaled when the object was slipping. This research effort demonstrated that when visual feedback is not available, the addition of tactile feedback relaying the occurence of slip significantly improves a person's ability to recover and prevent an object from falling out of his or her grasp. With this knowledge, vibrating feedback could be a valuable way to convey slip information from prosthetic grippers to prosthesis users, especially when visual attention is focused elsewhere.

2 METHODS

To test the effectiveness of vibratory tactile feedback of slip information for grasping tasks, an experiment was designed in which participants could interact with a virtual environment using a Sensable Phantom Desktop in a simplified grasping task.

2.1 Experimental Set-Up

The experimental set-up consisted of a Sensable Phantom Desktop for control and force feedback, a virtual environment displayed on a computer screen, and a vibrating C2 tactor (Engineering Acoustics, Inc., Casselberry, FL) strapped to each participant's upper arm for slip feedback. The set-up is shown in Figure 1. Users completed a virtual grasping task by controlling a cursor with the Phantom's stylus using their dominant hand. They pressed the cursor against a virtual object to hold it against a virtual wall, as shown in Figure 2. The goal was to prevent the object from slipping down the wall without breaking it. The plots in Figure 2 show the force applied to the object and the object's vertical position. When the object began to slip, the participant increased the force with which he or she was pressing until the slipping was successfully stopped and the object was recovered.

The C2 tactor was strapped to the upper part of each participant's dominant arm to relay tactile information on the occurrence of slip. The tactor was secured with a basic Velcro sports band for an mp3 player. The amplitude of the vibrations was proportional to the downward acceleration of the object. Pink noise was played to participants through headphones to mask sounds made by the vibrating tactor.

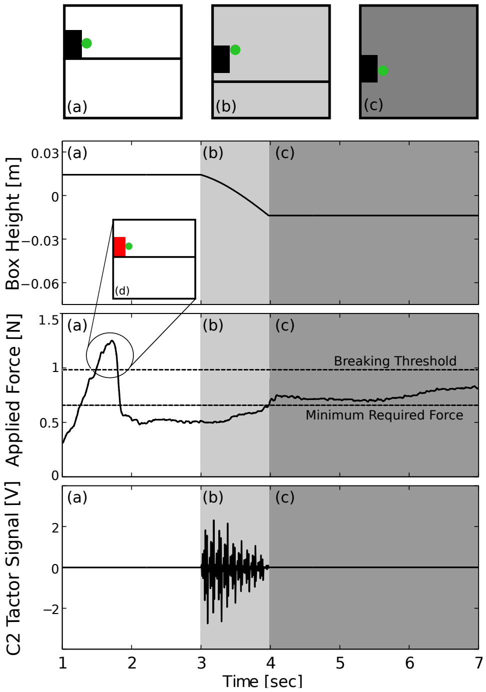

Figure 2: Example trial. (a) The floor has not yet fallen from under the object, so the object does not fall. During this time, the participant can set up the cursor in preparation. (b) The floor is falling, as is the object. The participant is not applying enough force to hold the object in place, so the object is slipping and the C2 tactor is vibrating with a maximum amplitude proportional to the object's acceleration. (c) The participant has increased the force against the object above the minimum required force, so the object has been recovered (is no longer falling). (d) When the force against the object is above the breaking threshold, the object turns red.

2.1.1 Simulation

The experiment was simulated with MatLab and a Simulink model employing the Sensable Phantom and Quarc Visualization Toolkits. The virtual environment consisted of a two-dimensional square room with a floor positioned halfway up the room, as shown in Figure 1(b). A rectangular object was positioned on the floor next to the left wall of the room. A circular cursor was the user controlled input to the environment. Each trial began with this initial set-up. After three seconds, the floor beneath the object fell to the bottom of the screen, as shown in the progression of screenshots in Figure 2(a)-(c). With no support from the floor, the participant had to press the cursor into the object against the wall to keep it from falling.

Over the course of the first three seconds, the user was expected to prepare by pushing the cursor against the object. During this time, the cursor changed from red to yellow to green, signaling to the user when the floor would fall. There were no cues given for incipient slip because the focus in this study was gross slip.

Each trial lasted a maximum of seven seconds, after which the environment would reset and the next trial would begin automatically. In cases where a participant failed to keep the object from falling, the trial ended early and was reset for the next trial as soon as the object touched the ground.

The cursor's position, controlled by the participant, was input by the position of the Phantom. The virtual task was designed to deal only with two dimensions, so one component of the position was disregarded (the distance forward from the user), and the cursor on the screen was only shown to move vertically and horizontally. Distances into and out of the screen were not portrayed.

The normal force on the object was calculated by

$$f(t) = K_p(x(t) - x_{obj}) + K_d\dot{x}(t) \tag{1}$$

where x represents the position of the Phantom, x_{obj} represents the location of the right face of the object,$K_p = 400$ N/m and $K_d = 4N \cdot s/m$. The force was only applied in the direction away from the object.

The velocity of the object was calculated by

$$v(t) = \begin{cases} \int \frac{f(t)\mu - mg}{m} dt & \text{if } mg > f(t)\mu \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where z is the vertical position of the object, g is the acceleration due to gravity set to 9.81 $\frac{m}{s^2}$, and μ is a friction constant set to 0.3. The value for μ was selected so that the rate of slipping was appropriate to allow participants to recover from slips. $f(t)$ is the normal force applied to the object, which was calculated by Equation 1. m is the mass of the object, which was set to either 0.2 kg or 0.5 kg depending on the trial. If the force due to static friction wasn't high enough to overcome the force due to gravity, the object experienced a positive acceleration toward the floor. The participant had to adjust to this slip by increasing the normal force against the object. There was no visual indication of the object weight, so participants had to adjust the applied force appropriately. The force required to prevent slip was 0.654 N for the lighter object and 1.64 N for the heavier object. 1 cm of movement of the Phantom was displayed as approximately 1.25 cm of movement on the computer screen.

During a trial, if the calculated force was above 1.5 times the force necessary to hold the object, the object turned red to signal to the participant that he or she was "breaking" it. The heavy object broke when the applied force exceeded 2.45 N and the light object broke with a force greater than 0.981 N. Figure 2(d) shows the object being broken during the time before the floor fell.

2.1.2 Visual Feedback

The visual feedback condition was turned on and off through the virtual environment to mimic use of a prosthesis while watching or not watching the gripper. During trials without visual feedback, the participant was able to see the object during the three-second set-up period, but as soon as the floor dropped, the object also disappeared. The participant had to attempt to hold it against the wall without being able to see where it was, if it was slipping from their grasp, or if it was breaking. The situation during which the user had no visual or haptic feedback is analogous to the use of a traditional prosthesis without paying visual attention to the gripper, because current prosthetic devices provide no touch feedback.

2.1.3 Vibrotactile Feedback

Vibrotactile feedback was applied through the vibrating tactor in the armband on each participant's upper arm. If the object was slipping, the current sent to the tactor was equal to

$$i(t) = 2(f(t)\mu - mg)s(t)sin(2\pi * 200t) \tag{3}$$

where $s(t)$ is a 10 Hz sawtooth wave, resulting in a vibrational pulse with a maximum amplitude proportional to the acceleration with which the object was falling. The magnifying constant 2 was selected to produce an appropriately prominent vibration. If the user held the object against the wall without any slipping, no vibrations would be felt. However, once the force was below the necessary level to prevent slip, the tactor began to vibrate, signaling to the participants that they needed to press harder.

2.1.4 Force Feedback

Force feedback was controlled through the Phantom. The force applied to the object was reflected to the participant through the Phantom's handle, simulating the feeling that there was a real object resisting the participant's motion. It also gave the participant an understanding of how hard he or she was pushing. When the force feedback condition was turned off, the force applied to the box was calculated by the same method to determine the object's acceleration but no force was applied back to the Phantom's handle. In this case, the participants had no sense of how hard they were pressing except in the visual feedback trials when they reached the breaking threshold and the object turned red.

2.2 Experimental Protocol

23 able-bodied individuals (17 male, 6 female) participated in this experiment. Before the experiment, subjects listened to a scripted description of the methods and provided informed consent. The study was conducted with healthy individuals rather than amputees because the sensations would be perceived in the same way for both able-bodied participants and amputees. The vibrating tactor was worn on the upper arm, where, in a transradial amputation, a prosthesis would meet the residual limb, making this a logical location for vibrotactile feedback to be implemented in a prosthesis.

2.2.1 Training

Before beginning the trials, each participant interacted with a practice environment for 20 seconds. The practice environment was a square room similar to the trial environment, but there was no object present. When the user pressed the cursor into any wall of the room, force feedback was applied to the Phantom and a visual display on the side of the room indicated force applied. In this way, participants were given the opportunity to familiarize themselves with force feedback from the Phantom. No vibrational feedback was applied during the practice session.

After the practice session ended, the participants completed three practice trials with the object during which they experienced both force feedback and vibrational feedback. After the third practice trial, there was a ten second pause during which the participant was instructed to put on headphones playing pink noise. The headphones were left off during the practice trials so that the experimenter could answer any questions.

2.2.2 Testing

The participant then completed the experimental trials. Figure 3 shows the design of the trials and the system used to vary the feedback conditions. Each participant completed 192 trials, divided into four blocks by the visual feedback condition. For two of the blocks, visual feedback was available (V), and for two blocks it was not (v). For all of the participants, the first block of 48 trials provided visual feedback to enable them to get used to the experiment. Of the second and third blocks, one was with vision and one was without. The fourth block was without visual feedback for all participants. The number of participants who had vision for block two was balanced with the number of participants who had vision for block three.

Within each block of 48 trials, four different combinations of haptic feedback were tested: force feedback only (Ft), tactile feedback only (fT), both force and tactile feedback (FT), and no feedback (ft). Blocks were organized into eight sets of six trials each with the same feedback condition, with each feedback condition occurring in two sets. The first group of four sets and second group of four sets were each sequences of the four possible force/tactile combinations. Six different possible sequences were used to arrange the order of the feedback conditions in a balanced way. This design resulted in each participant completing a total of 24 trials under each feedback combination.

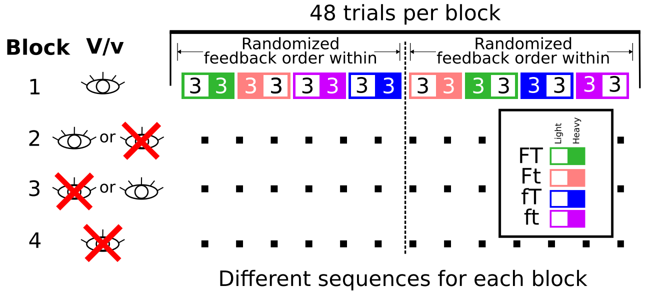

Figure 3: Visual representation of experiment design. Force and tactile combinations are depicted as different colors. Trials involving light and heavy objects are depicted as white boxes or filled boxes, respectively.

Within a set, three trials in a row involved heavy objects and three trials in a row involved light objects. The order of heavy and light objects was balanced among the occurrences of the feedback conditions in the six different sequences.

2.3 Analysis

The task performance metrics consisted of the number of slips and the percent recoveries by feedback condition. The percent recoveries value is defined as the number of recoveries divided by the number of slips. Any trial in which the object's vertical position at the end was lower than the initial position was counted as a slip. If a participant successfully increased the force on the object after the onset of slip and stopped the object from slipping to the bottom of the screen, the trial was also counted as a recovery.

To examine the effects of feedback condition on performance, one-way repeated measures Analysis of Variance (ANOVA) was performed on both the number of slips and the percent recovery, with feedback condition as the independent variable. The Geisser-Greenhouse (G-G) adjustment was used to correct for violations of the sphericity assumption. Significant effects were followed up with a Tukey-Kramer test for post-hoc comparisons with a significance criterion of 0.05. Cohen's d effect size indices were calculated and included to assess the practical significance of the findings. In addition, three specific complex comparisons were assessed for both dependent measures. First, to assess the impact of visual feedback on performance, the average vision scores were compared to the average no-vision scores for slips and percent recovery. Second, to assess the impact of tactile feedback on performance in the no-vision conditions, the average tactile feedback scores (vFT, vfT) were compared to the average no-tactile feedback scores (vFT, vFt). Third, to determine the influence of force feedback on performance, a complex comparison of the force feedback (vFT, vFt) versus the no-force feedback (vfT, vft) conditions was made in the no-vision conditions. To control for Type I error rates throughout the experiment, false detection rates (FDR) were applied to the multiple comparisons across both dependent measures [5]. Number Cruncher Statistical Software 2008 (www.ncss.com) was used for the statistical tests.

3 RESULTS

We analyzed the effect of feedback condition on (1) the number of virtual object slips that occurred and (2) subjects' ability to recover the virtual object upon the onset of slip. In this paper, we have not analyzed other experimental factors such as the effect of object weight and the occurrence of the object breaking. These factors will be explored in future work.

3.1 Number of Slips

The number of slips experienced by all subjects under each feedback condition (out of a possible 24 trials) is shown in Figure 4.

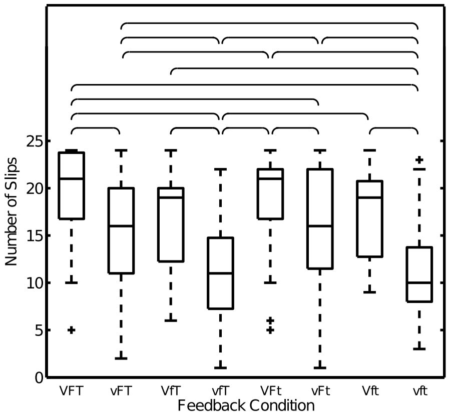

Figure 4: Number of slips for each feedback condition across subjects. Feedback condition labels represent vision or no vision (V or v), force or no force (F or f), and tactile or no tactile (T or t). Brackets indicate statistically significant pairwise comparisons.

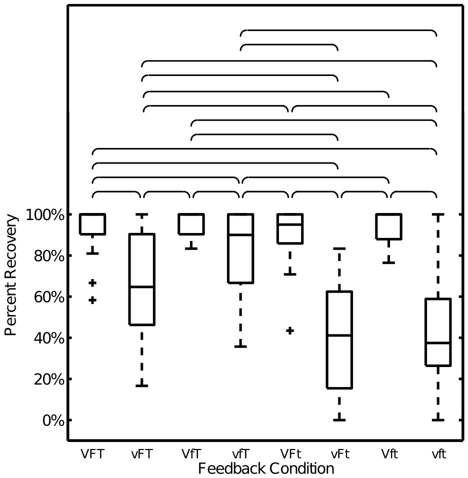

Figure 5: Percent recovery from slip for each feedback condition across subjects. Feedback condition labels represent vision or no vision (V or v), force or no force (F or f), and tactile or no tactile (T or t). Brackets indicate statistically significant pairwise comparisons.

One-way repeated measures ANOVA showed a significant effect of feedback condition ($F(7,154) = 16.09$, $p < 0.001$ (G-G), partial $\eta^2 = 0.44$). Significant pairwise comparisons with a family-wise α level of 0.05 are indicated with brackets in Figure 4. Subjects generally experienced more slips with visual feedback than without, and when visual feedback was not available they experienced more slips with force feedback than without. The slip count means, standard deviations, and effect sizes are shown in Table 1.

As shown in Figure 4, all subjects experienced slip under all feedback conditions, allowing calculation of a percent recovery for each subject under each feedback condition. Although some subjects experienced relatively few slips under some feedback conditions, most subjects experienced slips in at least 25% of trials under most feedback conditions, and the large sample size ($n = 23$ subjects) allows for reliable analysis of the percent recovery over all subjects.

3.2 Percent Recovery from Slips

The percent recovery from slips by all subjects under each feedback condition is shown in Figure 5. The one-way repeated measures ANOVA for feedback condition was significant ($F(7,154) = 46.78$,

Feedback Group	*Mean*	*SD*	*d*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	19.43	5.16	0.107	0.483	0.364	0.776	0.669	1.539	1.555
VFt	18.86	5.53		0.363	0.239	0.662	0.557	1.382	1.397
VfT	16.87	5.44			-0.155	0.345	0.239	1.024	1.040
Vft	17.65	4.61				0.505	0.392	1.266	1.283
vFT	14.74	6.92					-0.094	0.553	0.567
vFt	15.39	6.92						0.659	0.673
vfT	11.35	5.34							0.017
vft	11.26	5.35							

░	trivial effect	0.00 - 0.15
░	small effect	0.16 - 0.49
▒	moderate effect	0.50 - 0.79
▓	large effect	0.80 - 1.49
█	very large effect	> 1.50

Table 1: Descriptive statistics and Cohen's d effect sizes for all paired comparisons for number of slips.

Feedback Group	*Mean*	*SD*	*d*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.932	0.111	0.203	-0.403	-0.264	1.443	2.818	0.729	2.659
VFt	0.907	0.135		-0.629	-0.476	1.232	2.519	0.514	2.368
VfT	0.963	0.043			0.123	1.961	3.661	1.229	3.472
Vft	0.956	0.071				1.757	3.307	1.036	3.131
vFT	0.660	0.266					0.947	-0.744	0.828
vFt	0.412	0.258						-1.890	-0.125
vfT	0.826	0.180							1.752
vft	0.444	0.256							

░	trivial effect	0.00 - 0.15
░	small effect	0.16 - 0.49
▒	moderate effect	0.50 - 0.79
▓	large effect	0.80 - 1.49
█	very large effect	> 1.50

Table 2: Descriptive statistics and Cohen's d effect sizes for all paired comparisons for percent recoveries.

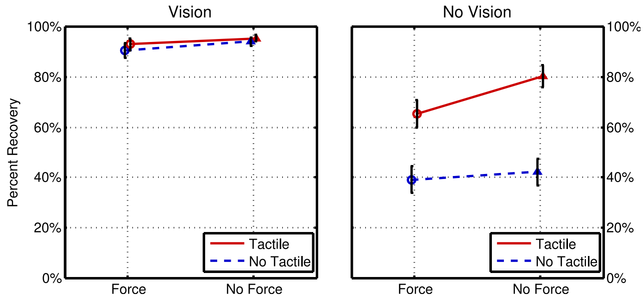

Figure 6: Percent recovery from slip for each feedback condition across subjects for the vision and no-vision conditions. Error bars represent standard error across subjects within each feedback condition. No-vision conditions highlight the importance of tactile feedback when not visually monitoring object position; tactile feedback improves the percent recovery both with and without force feedback.

$p < 0.001$ (G-G), partial $\eta^2 = 0.68$). Significant pairwise comparisons with a family-wise α level of 0.05 are indicated with brackets in Figure 5. The percent recovery means, standard deviations, and effect sizes are shown in Table 2. The large effect sizes ($d >= 0.80$ standard deviation units) illustrate the increase in percent recoveries with visual feedback.

The three complex comparisons were significant. The vision feedback conditions had significantly greater percent recoveries than the no-vision conditions ($t(154) = 9.52, p < 0.001$), whereas under the no-vision conditions, tactile feedback conditions had greater percent recoveries than the no-tactile feedback groups ($t(154) = 5.52, p < 0.001$) and the force feedback groups had significantly less percent recoveries than the no-force feedback groups ($t(154) = 6.00, p < 0.001$). In the no-vision conditions, the tactile feedback condition (vfT) had the highest percent recovery and the lowest variability (see Table 2). Importantly, the tactile feedback condition without vision had a very large effect ($d = 1.752$) when compared to the no feedback condition (vft).

Figure 6 shows a different view of the percent recovery statistics, separating by vision and no-vision conditions. With visual feedback, the effects of force feedback and tactile feedback are small. Without visual feedback, tactile feedback has a much larger effect on recovery from slip, significantly improving the percent recovery both with and without force feedback.

4 DISCUSSION

This study aimed to investigate the value of vibratory tactile feedback of slip information for object manipulation, focusing on a simple grasp and lift task. While others have used tactile feedback to encode grip force [6, 7, 10], we examined the utility of providing tactile feedback during object slip, and studied the corresponding impact on task performance. Our primary interest in this task is the ability of a person, under different feedback conditions, to recover an object that begins to slip. Though tactile feedback of slip information was the condition of most interest, we also studied tactile feedback in combination with visual feedback and force feedback to learn how the availability of other types of feedback affects the importance of slip information. We hypothesized that tactile feedback of object slip would benefit grasp and lift task performance.

The number of slips showed significant variation across feedback conditions, as shown in Figure 4. In particular, the number of slips was much higher without visual feedback. In these cases, subjects lacked the visual indication of the object breaking (see Figure 2(d)), so they tended to apply more force than necessary to hold the object. This resulted in fewer slips, but more breaking of the object. Further, subjects experienced significantly more slips with force feedback than without when visual feedback was not available. Without force feedback, subjects struggled to precisely regulate their applied force and often applied excessive force, as has been similarly observed in physical grasp and lift tasks [16]. This tendency to exert higher forces than necessary resulted in more breaking and less slipping. The availability of tactile feedback had only a trivial effect on the number of slips as shown in Table 1. This result is expected, because tactile feedback is only active after slip occurs.

Despite the variation in number of slips across feedback conditions, all subjects experienced slip under all feedback conditions, and most subjects experienced at least five slips (out of a possible 24) under most feedback conditions. Thus, with the large subject pool tested, the number of slips was still large enough to examine the recoveries from slips in all feedback conditions. As shown in Figures 5 and 6, the percent of trials that subjects recovered from slips, stopping the object from hitting the ground, varied significantly by feedback condition. With visual feedback available, subjects had higher recovery percentages than without visual feedback, regardless of whether force and tactile feedback were available. In the visual feedback cases, the change in object position is immediately and clearly visible to subjects, allowing them to quickly respond by increasing the force and preventing further slip.

While knowledge of the effect of all feedback modalities on performance of the grasp and hold task is valuable, our primary interest is the real-world scenario of a prosthesis user trying to manipulate an object while not visually attending to the gripper. In our study, this scenario corresponds to the case of no visual feedback. In the conditions without visual feedback, both force and tactile feedback had significant effects on subjects' ability to recover from slip. Without visual feedback, there is a clear benefit of the added tactile cue to convey slip. Vibrotactile feedback of slip occurrence drastically improved the percent recoveries both with and without force feedback. When vision and force were both off, the mean percentage of slips recovered increased from 42% to 80% with the addition of tactile feedback. When vision was off and force was on, it increased from 39% to 65% with tactile feedback. Clearly, without visual feedback, subjects were able to rely on the tactor's vibrational cues to infer slip information and adjust their grip accordingly, and the effect on performance was large (see Table 2). These results suggest the utility of tactile feedback of slip information for prosthesis use; although tactile feedback did not have a large effect on slip recovery performance when visual feedback was available, it had a significant and large effect on performance in the absence of visual feedback. In contrast, for those conditions with visual feedback available, neither force nor tactile feedback significantly affected subjects' ability to recover from slip, perhaps because there was little room for improvement to begin with. Participants were able to quickly adjust to slips by watching the object whether they felt vibrational feedback or not. Previous work has shown that even with comparable resolution, visual feedback may be more effective than tactile feedback for displaying motion information [22]. Nonetheless, tactile feedback provides an effective alternative when visual feedback is unavailable.

5 CONCLUSION

In this study, we examined the importance of vibratory tactile feedback of slip information in combination with visual and/or force feedback in a virtual grasp and hold task. This task was chosen as an interesting example of object manipulation because it required coordination between grip and load force while accounting for object weight. The results showed that when visual feedback is not available, the addition of tactile feedback relaying the occurence of slip significantly improves a person's ability to recover from the slip. With this knowledge, vibrating feedback could be a valuable way to convey slip information from prosthetic grippers to prosthesis users, especially when visual attention is focused elsewhere.

In future work, we will expand our analysis of these results to consider the various strategies that participants used to complete the task, the occurrence of breaking, and the effect of transitioning between objects of different weights. Studying these factors will provide further insight into how and why slip feedback may be useful to prosthesis wearers and how to best integrate slip feedback with other forms of feedback for advanced prosthesis systems.

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