Tactile Feedback of Object Slip Facilitates Virtual Object Manipulation

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Abstract—Recent advances in myoelectric prosthetic technology have enabled more complex movements and interactions with objects, but the lack of natural haptic feedback makes object manipulation difficult to perform. Our research effort aims to develop haptic feedback systems for improving user performance in object manipulation. Specifically, in this work we explore the effectiveness of vibratory tactile feedback of slip information for grasping objects without slipping. A user interacts with a virtual environment to complete a virtual grasp and hold task using a Sensable Phantom. Force feedback simulates contact with objects, and vibratory tactile feedback alerts the user when a virtual object is slipping from the grasp. Using this task, we found that tactile feedback significantly improved a user's ability to detect and respond to slip and to recover the slipping object when visual feedback was not available. This advantage of tactile feedback is especially important in conjunction with force feedback, which tends to reduce a subject's grasping forces and therefore encourage more slips. Our results demonstrate the potential of slip feedback to improve a prosthesis user's ability to interact with objects with less visual attention, aiding in performance of everyday manipulation tasks.

Index Terms—haptics, prosthetics, slip feedback, vibrotactile feedback

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1 INTRODUCTION

DESPITE recent advances in prosthetic technology, upper limb prostheses lack the touch feedback that is necessary for dexterous manipulation of objects. Current prosthetic hands have comparable motor function to natural limbs (for example, the DEKA arm, recently approved by the FDA [1]), but users are unable to adequately control them due to a lack of sensory feedback. If sensory function could be restored as effectively as motor function has been, the performance of upper limb prostheses could approach that of natural limbs.

One major innovation in prosthetic technology has been the incorporation of myoelectric control. Electromyographic (EMG) sensors detect electrical activity of muscle tissue in the residual limb. However, this approach eliminates the limited touch feedback that was available in body-powered prosthetic limbs, where cable tension gives users an indirect afferent pathway for information from the endpoint of a prosthetic gripper. In contemporary myoelectric devices, vision serves as the main source of feedback. Users would prefer to rely less on vision [2] because carefully watching a prosthetic gripper is mentally taxing, inefficient, and insufficient for replacing the information collected by natural touch sensations. Levels of mental workload in human-machine interaction can be quantified through brain imaging techniques (e.g., [3]) and questionnaires (e.g., [4]), and it has been shown that purely visual control of a prosthesis requires more mental effort than control with additional feedback cues [5].

Multi-function prosthetic hands have the potential to enable dexterous manipulation, but it is critical to modulate force and tactile feedback to the user to achieve such performance. The benchmark task for investigating manipulation and dexterity is the grasp-and-lift task, in which participants are asked to grip an object with their fingers on either side of the object, lift the object, and place the object back down on a surface. To evaluate the potential of tactile feedback to improve dexterity, we contend that it is logical to begin with this traditional task.

In an intact upper limb, receptors in the skin, joints, and muscles can sense object weight or detect an object slipping from the grasp, and this information is delivered to the central nervous system via afferent neural pathways. Typically, an individual maintains a grip force just slightly above what is necessary to prevent slipping. Cutaneous sensations from the fingertips enable a user to detect slip, gain information about object friction, and update an internal model of the object [6]. An able-bodied individual naturally processes this information and uses it to control motor commands to adjust their grasp, to handle an object without breaking it or dropping it. An upper-extremity amputee has no afferent or efferent pathways past the farthest point of the residual limb, making this transfer of information and intentions impossible.

Cutaneous sensations are considered to be more valuable to performance than vision for tuning motor output to the object properties [7]. Shear strain on the finger pads and vibrations caused by minute slips signal unwanted movement to the user [8]. Effective scaling of grip force relies predominantly on sensory information from the fingertips. Individuals completing a grasp and lift task without fingertip sensory feedback to collect slip information grip an object with a higher than

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necessary force before lifting it, often breaking the object [9], [10]. Thus, when an individual adapts to changing load forces or object properties, tactile information plays a major role in grasp and lift performance [11], [12].

Several current advanced prosthetic hands employ automatic control of grip force, in which grip is adjusted without user input based on sensed interactions with the object being grasped [13], [14]. This automatic control aids in preventing the breaking and dropping of objects being grasped; however, it will not facilitate general dexterous movements, which is our ultimate goal. Including the user in the control loop by providing touch feedback is necessary to improve an amputee's dexterity with a prosthesis. Although feedforward and feedback mechanisms play complementary roles in prostheses, the feedforward system's inevitable uncertainty can be corrected by the user with the inclusion of feedback [15]. Performance in manipulating objects with a prosthesis improves with more interactive control, implying that some combination of automatic control and user feedback may provide the most dexterity [16].

Given the importance of cutaneous feedback in slip and the benefit of including the user in the loop, we believe relaying natural slip information will improve user performance. Some techniques have been developed to electrically stimulate afferent nerves within the residual limb [17], but surgical risks and signal degradation make this method non-ideal. Non-invasive alternatives for feeding back some components of touch include sensory substitution via force, tactile, and skin stretch actuators (e.g., [16], [18], [19], [20]). Some of these methods aid in grasping with prosthetic hands; for example, vibratory tactile feedback and force feedback have been used to display grip force [21], [22], [23]. Texture information has also been relayed as vibrotactile feedback to users controlling a prosthetic gripper [24]. Additionally, vibrating feedback has shown promise for relaying proprioceptive feedback, improving performance operating a gripper particularly when subjects were distracted by other tasks [25]. Very little research has been done thus far on non-invasively feeding back slip sensations. Damian et al. found that electrotactile stimulation corresponding to object slip speed produced comparable results to visual feedback alone [26]. Promising results for the use of slip feedback have been shown in a laparoscopic surgical grasping task [27]. However, the surgical grasping system is not practical for prosthetics applications. In a study that delivered multimodal feedback to amputees with targeted reinnervation, researchers found that providing both force and shear feedback degraded manipulation performance [28]; however, this study provided all of the feedback through one multimodal haptic device. We believe that this could be confusing to the user, and it is beneficial to investigate performance when slip and force feedback are provided through separate modalities.

We explore the efficacy of a slip feedback system that would be practical for prosthesis use through a human subject experiment performed within a virtual environment. Our study investigates the use of tactile feedback via vibrating tactors to impart information about object slippage to the user of the system. Vibrotactile feedback was chosen to convey slip information because of its verified value for conveying other types of haptic information like force and proprioception, even when individuals are distracted [21], [25], [29], [30]. Our investigation centers on the grasp and lift task as a first step toward more dexterous manipulation. A simplified grasp and hold task was created in a virtual environment in which force feedback was provided that correlated to gripping force, and vibrational cues on the user's upper arm signaled when the object was slipping. Because we are focused on the effect of vibrotactile feedback in this study, we selected this virtual task to be an intuitive, easy-to-use alternative to a physical prosthesis system. Although this modified grasping task does not perfectly recreate interactions between a prosthetic hand and real-world objects the results are valuable for understanding the role of haptic feedback in preventing object slip.

We previously presented preliminary results from this study [31], demonstrating that the addition of tactile feedback relaying the occurrence of slip significantly improves a person's ability to recover an object that has begun to slip, particularly when visual feedback is not available. Here, we present an expanded analysis and discussion of additional factors, including the user's response after the onset of slip and the effect of feedback condition after unanticipated changes in object weight on performance. These results suggest that incorporating tactile feedback into advancing prosthetic technology could allow prosthesis users to enjoy greater dexterity and an increased ability to efficiently complete daily tasks.

2 METHODS

To test the effect of vibrotactile slipping cues in grasp and lift tasks, we developed a simplified "grasp and hold" task in a virtual environment. The user must grip the object firmly enough so it does not slip from his or her grasp, but gently enough so it does not break (similar to a plastic cup that can be dropped or crushed). We asked participants to complete the task using a Sensable Phantom as an input to press a virtual object against a wall. The goal was to modulate the force against the object to prevent it from slipping down the wall while pressing lightly enough so as not to break it.

This task differs from a traditional grasp and lift task because users press against an object from only one side, holding it in place rather than lifting it up. Additionally, they interact with the virtual object through a tool (the stylus of the Phantom Desktop), which is different from object manipulation in the physical world with a prosthetic hand. This simplified task required coordinating grip force and load force with object weight, as in a physical grasp and lift task. Therefore, we expect users to benefit from the same types of force and tactile information, and we use this scenario to evaluate different combinations of force, tactile, and visual feedback. When holding a real object, modulating force to stay between these two thresholds is natural and easy for individuals with intact sensory feedback. For prosthesis users, the lack of force and slip information makes breaking or dropping objects common. Our virtual task mirrored this object-force modulation situation, requiring users to control the force against the virtual object with all combinations of force feedback, vibrotactile slip feedback, and visual feedback.

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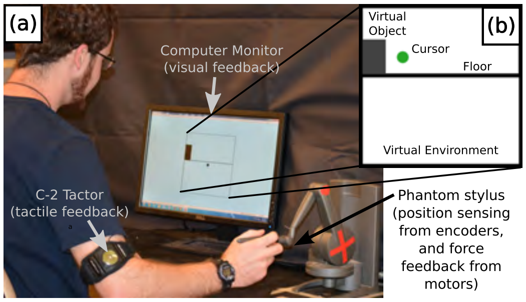

Fig. 1: (a) Experimental set-up. The user controls the cursor with the Phantom using his or her dominant hand to interact with the virtual environment displayed on the screen. The Phantom also provides force feedback. Slip feedback is provided via the C2 tactor worn on the dominant arm. Headphones play pink noise to mask auditory cues. (b) Virtual environment at the start of each trial. The participant controls the cursor position. The floor falls after three seconds, so the participant must press the cursor against the object to keep it from falling as well.

2.1 Experimental Set-Up

The experimental set-up, shown in Figure 1, 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 the participant's upper arm relaying tactile information on the occurrence of slip. Users interacted with the virtual environment on the computer screen by controlling a cursor with the Phantom's stylus. They pressed the cursor against a virtual object to hold it against a virtual wall. The plots in Figure 2 show the object's vertical position, force applied to the object, and the signal sent to the C2 tactor during an example trial. In this example, when the object began to slip, the participant increased the force applied until the slipping stopped and the object was recovered.

The C2 tactor was placed on the outer arm, in contact with hairy skin. For a transradial amputee, the upper arm is a logical choice of location for haptic feedback because of its proximity to the hand. The tactor was secured with a Velcro sports band for an mp3 player. The amplitude of the vibrations was proportional to the acceleration with which the object was slipping down the wall. The amplitude was adjusted to be both noticeable and comfortable to the user through the sports band. To mask sounds made by the vibrating tactor, pink noise was played to participants through headphones.

2.1.1 *Simulation*

The virtual environment and feedback were controlled 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 that floor against the left wall of the room. A circular cursor corresponded to the Phantom's stylus position, which was the user controlled input to the environment. Because the virtual environment was limited to 2-D, horizontal and vertical movements of the Phantom's stylus were mapped to cursor location, while movements into and out of the screen were not portrayed. Each trial began with this initial set-up.

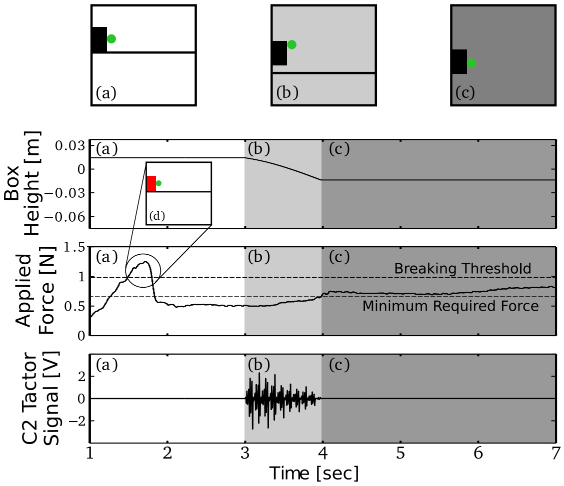

Fig. 2: Example trial. (a) The floor is fixed, so the object does not fall. During this time, the participant can set up the cursor in preparation. (b) The floor falls away. The participant is not applying enough force to hold the object, so the object is slipping and the C2 tactor is vibrating. (c) The participant has increased the force against the object above the required force to prevent slipping, so the object has been recovered. (d) When the force is above the breaking threshold, the object turns red.

After three seconds, the floor holding up the object fell to the bottom of the screen, as shown in the progression of screenshots in Figure 2(a)-(c). Without the support of the floor, the object would begin to fall unless the participant had used the Phantom stylus to press the cursor into the side of the object, pushing it against the wall and preventing it from slipping. Over the course of the first three seconds, before the floor dropped, the cursor changed from red to yellow to green, signaling to the user when the floor would fall. Each trial lasted a maximum of seven seconds, after which the environment reset and the next trial began automatically. In cases in which a participant failed to keep the object from falling to the ground, the trial stopped early and was reset for the next trial as soon as the object touched the ground.

The normal force $f(t)$ on the object was calculated using the position and velocity of the cursor when in contact with the right face of the object, and is given 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, the proportional gain $K_p = 400$ N/m, and the derivative gain $K_d = 4$ N·s/m. The resulting force to the user was only applied normal to the object's surface, resisting further penetration by the stylus. The proportional and derivative gains were selected to make the object's stiffness feel realistic.

The acceleration of the object $a(t)$ was calculated by

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

where g is the acceleration due to gravity set to 9.81 m/s^2, and μ is a friction constant set to 0.3, similar to the coefficient of friction between a human finger and a piece of paper [32],

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[33] or the lacquered aluminum used in some jar lids [34]. The value for the virtual friction constant μ was selected so that the rate of slipping was not too fast for participants to adjust the applied force and recover the object once it began to slip. The normal force $f(t)$ applied to the object was calculated by Equation 1. The mass m of the object 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 to account for weight differences. With these selected values, 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.

When holding objects with prosthetic hands, a common strategy is to grip with much higher force than necessary to prevent dropping the object, often resulting in damage to the object [35]. To prevent study participants from using the same strategy, the virtual object was made to be breakable. 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. When a participant broke the object, the color changed while breaking was occurring but participants continued for the full duration of the trial.

2.1.2 Visual Feedback

Visual feedback consisted of the object position and the cursor position. Movement of the object indicated slip, and color of the object indicated when the object was breaking (red while breaking, black otherwise). The visual feedback condition was turned on and off through the virtual environment to mimic the use of a prosthesis while watching or not watching the gripper. For no vision trials, the participant was able to see the object during the three-second set-up period, but as soon as the floor dropped, the object 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 cursor was still visible to the user in the non-visual feedback condition. In the event that the object slipped out of the user's grasp, the reaction force against the cursor became zero and the cursor moved through the space the object had vacated to hit the left wall. In trials when there was no visual, force, or tactile feedback, this movement of the cursor was the only indication to the user that they had dropped the object.

2.1.3 Vibrotactile Feedback

Vibrotactile feedback was applied through the vibrating tactor in the armband on the participant's upper arm. The current sent to the tactor was computed as

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

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 slipping. Sawtooth waveforms are more easily detectable by humans than smooth sinusoidal waveforms [36]. The magnifying constant $A = 2$ was selected to produce an appropriately prominent vibration. Pacinian Corpuscles have peak sensitivity for frequencies from 200-300Hz, and for this tactor applying this waveform, a frequency of 200Hz was found to be both comfortable and noticeable. 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 object accelerated downward and the tactor began to vibrate, signaling to the participant to press harder. The amount of force necessary to stop a slipping object was directly proportional to the amplitude of the vibrations felt by the user.

2.1.4 Force Feedback

The force applied to the object was reflected to the participant through the Phantom's stylus, simulating the feeling that there was a real object resisting the participant's motion. It gave the participant an understanding of how hard he or she was pressing on the object. When the force feedback condition was turned off, the force applied to the object was calculated to determine the object's acceleration but no force was applied back to the Phantom's stylus. In this case, the participants had no physical sense of how hard they were pressing against the object. In trials with the visual feedback condition on, the object turned red if the participant was pressing hard enough to break it, relaying some force information visually.

2.2 Experimental Protocol

Twenty-three ($n = 23$) able-bodied individuals (17 male, 6 female, ages 18 to 30) participated in this experiment. Before the experiment, subjects listened to a scripted description of the methods and provided informed consent. Subjects used their self-reported dominant hand to complete the task.

2.2.1 Training

Before beginning the trials, each participant was given 20 seconds to interact with an orientation environment: a square room similar to the trial environment, but with no virtual object. It allowed participants to become familiar with the Phantom and the force feedback. When pressing the cursor against the room's walls, force was applied to the stylus and a visual display indicated the force's magnitude. No vibrational feedback was applied during the orientation session.

After this orientation session ended, participants completed three practice trials in the actual study environment. During these practice trials, force feedback, vibrotactile slip feedback, and visual feedback were all provided. The headphones were left off during the practice trials so that the experimenter and participant could speak to each other. After the third practice trial, there was a ten second pause during which the participant was instructed to put on headphones playing pink noise.

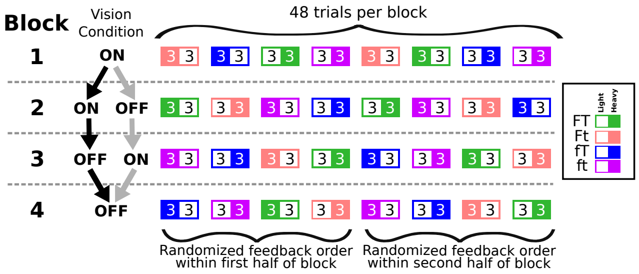

Fig. 3: Experiment design. Participants completed four blocks of trials, shown above as rows of colored rectangles. Each block of 48 trials contained 8 sets of 6 trials each. Each colored rectangle represents a set. Each set had a constant feedback condition for all six trials, depicted by the color, and consisted of three consecutive trials with heavy objects (filled boxes) and then three consecutive trials with light objects (white boxes), or vice versa. Within each block (each row above), participants completed two sets of each of the four haptic feedback combinations. The four blocks differed by the vision condition being on or off, and each had a different balanced order of the haptic feedback sets.

2.2.2 Testing

The participant then completed the experimental trials. Figure 3 shows the experiment design and the organization of feedback conditions. Each participant completed 192 trials, divided into four blocks by the visual feedback condition. For two of the blocks, visual feedback was provided (V), and for the other two blocks it was not (v). The visual feedback condition was constant for the duration of the 48 trials in a block. For all of the participants, the first block provided visual feedback. This allowed them to familiarize themselves with the experiment. Of the second and third blocks, one was with vision and one was without, in either order. The number of participants who had vision for block two was balanced with the number of participants who had vision for block three. The fourth block was without visual feedback for all participants.

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. In each set, the six trials had a constant feedback condition. The four force/tactile combinations were each provided for two of the eight sets in a block. The first group of four sets and second group of four sets were 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.

Each set had three consecutive trials with heavy objects and three consecutive trials with light objects. The first trial after a weight change (heavy-to-light or light-to-heavy) within a set represents an unanticipated change in object weight. We call this a *transition trial*. The order of heavy and light objects was balanced among the occurrences of the feedback conditions in the six different possible sequences. Participants encountered a light-to-heavy transition and a heavy-to-light transition either two or three times for each feedback condition over the course of the experiment. The two objects had no visible differences, but the force thresholds for dropping and for breaking the object were different. This ordering allows us to explore users' abilities to adjust to unexpected weight changes with each of the feedback combinations.

2.3 Analysis

The task performance metrics are % recovery, % time slipping, % response to slip, mean force, and % broken, defined as follows. 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. *% recovery* is then defined as the number of recoveries divided by the number of slips. *% time slipping* is defined as the amount of time the object was slipping during a trial divided by the total trial length. If the object slipped to the bottom of the screen before the full seven seconds had passed, the trial ended early, resulting in a shorter total trial length. *% response to slip* is defined as the percentage of slip trials in which the subject responded with an increase in force before the end of the trial, regardless of whether the object was actually recovered. To classify an intentional response to slip, a force increase threshold of 0.4167 N/s (chosen based on visual classification of reactions in randomly selected trials) was used to distinguish between small involuntary force changes and a voluntary reaction. *Mean force* is defined as the mean force over the course of a trial. *% broken* is the percentage of trials in which the object was broken at some point during the trial. We considered both *% broken* over all trials and *% broken* over trials in which the object was recovered from slip. *% recovery* and *% time slipping* were also examined for effects of feedback after weight transitions. There are two categorizations regarding responses to weight transitions: (1) light-to-heavy (LH) object transition and (2) heavy-to-light (HL) object transition.

For all analyses, the assumptions of the repeated measures Analysis of Variance (ANOVA) were inspected and addressed, and feedback condition was a fixed effect, within-subjects independent variable. The Geisser-Greenhouse (G-G) adjustment was used to correct for violations of the sphericity assumption. Post-hoc comparisons used a Tukey-Kramer test 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 the dependent measures. (1) The average of vision scores (VFT, VFt, VfT, Vft) was compared to the average of no vision scores (vFT, vFt, vfT, vft). (2) In the no vision conditions, the average of tactile feedback scores (vFT, vfT) were compared to the no tactile feedback (vFt, vft). (3) Force feedback (vFT, vFt) was compared to no force feedback (vfT, vft) in the no vision conditions.

The effect of feedback condition after weight transitions on performance was assessed on *% recovery* and *% time slipping* in the transition trials. Transition trials include the first trial after an object weight change within a set of trials with the same feedback condition. Two separate one-way repeated measures ANOVAs were performed for light-to-heavy and heavy-to-light transition trials. One complex comparison assessed

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the influence of tactile feedback during weight transitions in the no vision condition. One paired comparison assessed the importance of tactile feedback when no other feedback is available by comparing tactile feedback only (vfT) to no feedback (vft). A second paired comparison assessed the relative importance of force feedback and tactile feedback in the absence of vision by comparing force feedback only (vFt) to tactile feedback only (vfT). The complex comparison assessed the influence of any tactile feedback by comparing the average of tactile feedback cases in the no vision condition (vfT, vFT) to the no feedback case (vft). For the transition conditions, multiple imputation methods were used to replace missing *% recovery* values with the mean value within each feedback condition [37].

To control for Type I error rates throughout the experiment, false detection rates (FDR) were applied to the multiple comparisons across the dependent measures [38]. Number Cruncher Statistical Software 2009 (www.ncss.com) was used for the statistical tests.

3 RESULTS

We analyzed the effect of feedback condition on (1) a subject's ability to recover the virtual object upon the onset of slip, (2) the percentage of time that the object was slipping during a trial, (3) the percentage of slip trials in which a subject responded before the end of the trial (regardless of whether the object was recovered), (4) the average force over the course of a trial, (5) the percentage of trials in which the object was broken, and (6) the percentage of recovery trials in which the object was broken. We also analyzed the effect of feedback condition after object weight changes on a subject's ability to recover the virtual object upon the onset of slip and the percentage of time that the object was slipping during a trial.

The results for *% recovery*, *% time slipping*, and *% response to slip* are reported with $n = 23$, as there were no outliers. The results for *mean force*, *% broken overall*, and *% broken within recovery trials* are reported with $n = 22$, since one subject had outliers for two of the no vision (vfT and vft) conditions ranging from greater than 2 to 325 times the variance of the next highest and lowest groups. We re-ran the analyses with this subject removed and compared the results to the output from the full sample size. All of the measures yielded comparable output (i.e., the main effects and contrasts were significant and there was a similar directional change).

Table 1 provides means and standard deviations for the various metrics, and significant pairwise comparisons are shown in Table 2. Effect sizes are given in the Appendix.

3.1 Percent Recovery from Slips by Feedback

In our preliminary analysis [31], we considered the number of slips that occurred under each feedback condition to ensure that a sufficient number of slips occurred for *% recovery* calculations and analysis. All subjects experienced slip under all feedback conditions, allowing calculation of a *% 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 the trials under most feedback conditions, and the large sample size ($n = 23$ subjects) allows for reliable analysis of *% recovery* over all subjects. *% recovery* from slips by all subjects under each feedback condition is shown in Figure 4(a). The one-way repeated measures ANOVA for feedback condition was significant ($F(7,154) = 48.76$, $p < 0.001$ (G-G), $\eta^2_{partial} = 0.69$). Significant pairwise comparisons are shown in Table 2 (see $\star$). The large effect sizes ($d >= 0.80$ standard deviation units, see Appendix) illustrate the increase in *% recovery* with visual feedback.

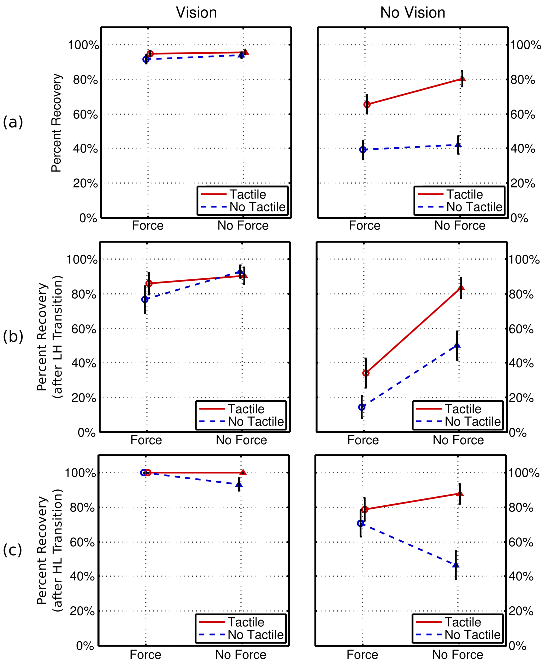

Fig. 4: *% recovery* from slip for each feedback condition across subjects ($n = 23$). Error bars represent standard error across subjects within each feedback condition. (a) The no vision conditions highlight the importance of tactile feedback when the subject is not visually monitoring the object: tactile feedback improves *% recovery* with or without force feedback. (b) After light-to-heavy object transitions, *% recovery* is lower in no vision conditions. Without visual feedback, tactile feedback help subjects recover from slip, whereas force feedback makes subjects less likely to recover a slipping object. (c) After heavy-to-light transitions, *% recovery* is lower in no vision conditions, but tactile feedback helps users recover with a frequency close to the vision condition. Without vision, force feedback improves *% recovery* in conjunction with tactile feedback.

The three complex comparisons were significant. The vision conditions had greater *% recovery* than the no vision conditions ($t(154) = 15.52, p < 0.001$). Under the no vision conditions, tactile feedback conditions had greater *% recovery* than no tactile feedback conditions ($t(154) = 9.49, p < 0.001$) and force feedback conditions had less *% recovery* than no force feedback conditions ($t(154) = 2.59, p = 0.010$). Of the no vision conditions, the tactile feedback condition (vfT) had the highest *% recovery* and the lowest variability (see Table 1). Importantly, the tactile feedback condition without vision had a very large effect ($d = 1.752$) when compared to the no feedback condition (vft).

Figure 4(a) shows the overall patterns in the *% recovery* statistics, separating vision and no vision conditions. With visual feedback, effects of force and tactile feedback are

	% Recovery Overall (⋆)	% Recovery after LH (●)	% Recovery after HL (◇)	% Time Slipping Overall (△)	% Time Slipping after LH (+)	% Response to Slip (†)	% Broken within Recovery (‡)
VFT	0.949 ± 0.080	0.857 ± 0.309	1 ± 0	0.295 ± 0.167	0.413 ± 0.261	0.946 ± 0.072	0.204 ± 0.116
VFt	0.916 ± 0.115	0.765 ± 0.368	1 ± 0	0.304 ± 0.174	0.510 ± 0.309	0.976 ± 0.035	0.273 ± 0.170
VfT	0.956 ± 0.057	0.904 ± 0.232	1 ± 0	0.171 ± 0.078	0.196 ± 0.166	0.938 ± 0.092	0.759 ± 0.129
Vft	0.941 ± 0.081	0.927 ± 0.165	0.932 ± 0.179	0.214 ± 0.072	0.281 ± 0.145	0.953 ± 0.081	0.741 ± 0.172
vFT	0.656 ± 0.264	0.341 ± 0.400	0.786 ± 0.327	0.349 ± 0.245	0.636 ± 0.363	0.833 ± 0.188	0.209 ± 0.222
vFt	0.392 ± 0.253	0.143 ± 0.307	0.706 ± 0.371	0.466 ± 0.281	0.701 ± 0.367	0.644 ± 0.278	0.239 ± 0.235
vfT	0.802 ± 0.208	0.833 ± 0.284	0.877 ± 0.288	0.166 ± 0.105	0.200 ± 0.247	0.853 ± 0.199	0.474 ± 0.278
vft	0.422 ± 0.253	0.500 ± 0.399	0.467 ± 0.383	0.279 ± 0.145	0.343 ± 0.382	0.625 ± 0.291	0.468 ± 0.363

TABLE 1
Descriptive statistics (mean ± standard deviation).

	VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT		△ ‡	‡	⋆ ●	⋆ ● ◇ △ + †	△ ‡	⋆ ● ◇ † ‡
VFt		△ + ‡	+ ‡	⋆ ● †	⋆ ● ◇ △ †	△ + ‡	⋆ ◇ † ‡
VfT				⋆ ● △ + ‡	⋆ ● ◇ △ + † ‡	⋆ ‡	⋆ ● ◇ † ‡
Vft				⋆ ● △ + ‡	⋆ ● △ + † ‡	‡	⋆ ● ◇ † ‡
vFT					⋆ †	● △ + ‡	⋆ ◇ + † ‡
vFt						⋆ ● △ † ‡	● ◇ △ ‡
vfT							⋆ ◇ †

TABLE 2
Significant pairwise comparisons. Symbols indicate significance at a family-wise α level of 0.05 for the following: ⋆ *% recovery overall*, ● *% recovery after LH transition*, ◇ *% recovery after HL transition*, △ *% time slipping overall*, + *% time slipping after LH transition*, † *% response to slip*, ‡ *% broken within recovery trials*.

negligible with an apparent ceiling effect on performance. Without vision, tactile feedback has a much stronger effect on recovery from slip, with improvements in *% recovery* ranging from moderately strong effects with force feedback ($d = -0.614$) to very large effects without force feedback ($d = -1.770$).

3.2 Percent Recovery after Weight Transitions

In addition to the effects of feedback conditions, effects of object transitions also impacted performance on percentage of slips recovered. We explored the effects of feedback conditions within light-to-heavy and heavy-to-light object transitions to determine how feedback conditions affected a subject's ability to interact with the object after weight changes, when slips and breaks were more likely. These scenarios are applicable to real-life situations in which a person picks up an object that is lighter or heavier than expected.

3.2.1 Light-to-Heavy Virtual Object Transitions

% recovery from slips after light-to-heavy transitions by all subjects under each feedback condition is shown in Figure 4(b). There was a significant effect of feedback condition ($F(7,154) = 21.88$, $p < 0.001$ (G-G), $\eta^2_{partial} = 0.50$). Significant FDR adjusted pairwise comparisons are reported in Table 2 (see ●). To assess the influence of tactile feedback under the no vision condition, comparisons were tested. The comparison of the no vision tactile feedback only condition (vfT) to the no feedback condition (vft) resulted in a significant comparison and a large effect ($d = 0.96$) favoring the tactile feedback. The comparison of the no vision, force feedback only condition (vFt) compared to the no vision, tactile feedback only condition (vfT) was also significant, with a very large effect ($d = 2.33$) favoring the tactile feedback. The complex comparison between no vision with tactile feedback (vfT, vFT) and no feedback (vft) was not significant.

Figure 4(b) illustrates the effects of different feedback types on *% recovery* in light-to-heavy object transitions. Without visual feedback, subjects are less likely to recover a slipping object; however, tactile feedback can help subjects recover the slipping object in a no vision situation. In this experiment, subjects were more likely to recover a slipping object without force feedback than with force feedback.

3.2.2 Heavy-to-Light Virtual Object Transitions

The *% recovery* from slips after heavy-to-light transitions by all subjects under each feedback condition is shown in Figure 4(c). There was a significant effect of feedback condition ($F(7,154) = 12.72$, $p < 0.001$ (G-G), $\eta^2_{partial} = 0.37$). Significant FDR adjusted pairwise comparisons are reported in Table 2 (see ◇). The comparison between tactile feedback only (vfT) and no feedback (vft) was significant, yielding a large effect ($d = 1.22$). This difference illustrates an advantage of tactile feedback (vfT) over no feedback (vft) when recovering from slips after a heavy-to-light object transition. The complex contrast indicated that the average *% recovery* of tactile feedback cases in the no vision condition (vfT, vFT) was significantly greater than *% recovery* in the no feedback condition (vft) ($t(154) = 5.66$, $p < 0.001$). The final paired comparison of the no vision force feedback (vFt) and the no vision tactile feedback (vfT) also showed the advantage for tactile feedback with a moderate effect ($d = 0.52$) favoring tactile feedback in recovering from slips.

Figure 4(c) shows the tendencies in *% recovery* after heavy-to-light object transitions. When visual feedback is available, *% recovery* is very high. Without visual feedback, *% recovery* is lower, but tactile feedback can improve *% recovery* to a rate close to that with visual feedback only. When neither tactile feedback nor visual feedback is available, force feedback improves *% recovery*.

3.3 Percent Time Slipping by Feedback

% time slipping for all subjects under each feedback condition is shown in Figure 5(a). In the analysis of *% time slipping*, there was a significant main effect of feedback condition

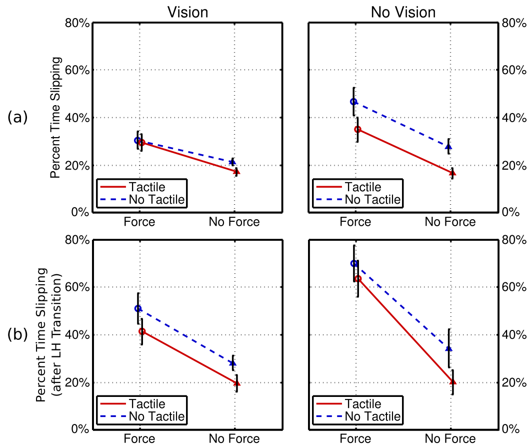

Fig. 5: *% time slipping* for each feedback condition across subjects ($n = 23$). Error bars represent standard error across subjects within each feedback condition. Subjects experienced more time slipping without visual feedback. (a) Overall, in no vision conditions, tactile feedback reduced *% time slipping*, whereas force feedback increased the *% time slipping*. (b) After light-to-heavy object transitions, visual feedback and tactile feedback tend to reduce *% time slipping*, whereas force feedback tends to increase *% time slipping*.

($F(7,154) = 13.18$, $p < 0.001$, $\eta^2_{partial} = 0.38$). Table 2 shows the significant differences found in the multiple comparisons (see △). The results of the complex contrasts show a significant difference between the vision and no vision conditions ($t(154) = 3.56$, $p = 0.001$). There was also a significant difference between the tactile and no tactile feedback in the no vision condition ($t(154) = 4.18$, $p < 0.001$) and between the force and no force feedback conditions for the no vision condition ($t(154) = 6.76$, $p < 0.001$).

Figure 5(a) shows the overall patterns in *% time slipping* across feedback conditions. Subjects experienced more time with the object slipping in three different conditions: (1) when visual feedback was not available, (2) when tactile feedback was not available in no vision conditions, and (3) when force feedback was available.

3.4 Percent Time Slipping after Weight Transitions

We also considered how feedback conditions affected *% time slipping* after weight transitions, when slips and breaks were more likely to occur. *% time slipping* after light-to-heavy transitions by all subjects under each feedback condition is shown in Figure 5(b). There was a significant effect of feedback condition ($F(7,154) = 13.32$, $p < 0.001$ (G-G), $\eta^2_{partial} = 0.38$). Significant FDR adjusted pairwise comparisons are reported in Table 2 (see +). Of the complex comparisons, the comparison of force feedback alone (vFt) to tactile feedback alone (vfT) was significant ($t(154) = 6.75$, $p < 0.001$) Figure 5(b) illustrates the effects of different feedback types on *% time slipping* in light-to-heavy object transitions. Visual feedback and tactile feedback tend to reduce *% time slipping*, and force feedback tends to increase *% time slipping*. No significant results were found for heavy-to-light virtual object transitions.

3.5 Percent Response to Slip

Figure 6 shows the percentage of trials with slip in which subjects responded to the slip before the end of the trial. There was a significant main effect of feedback condition ($F(7,154) = 18.49$, $p < 0.0001$ (G-G), $\eta^2_{partial} = 0.46$), with Table 2 showing significant pairwise comparisons (see †). Two complex contrasts were also significant. The comparison of vision feedback conditions to no vision feedback conditions was significant ($t(154) = 9.34$, $p < 0.001$), indicating that subjects were more likely to respond to slip with visual feedback than without it. The comparison of tactile feedback to no tactile feedback within the no vision condition was also significant ($t(154) = 6.42$, $p < 0.001$), indicating that subjects were more likely to respond to slip in the absence of visual cues when tactile feedback was provided. The effect of force feedback in the no vision condition was not significant. These effects are illustrated in Figure 6.

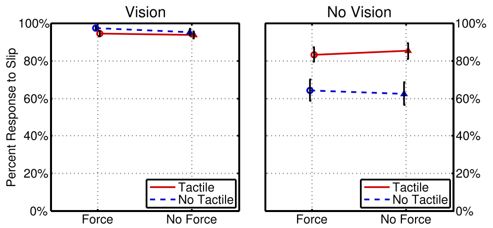

Fig. 6: *% response to slip* across subjects ($n = 23$). Error bars represent standard error across subjects within each feedback condition. In the no vision conditions, subjects were more likely to respond to slip when tactile feedback was available.

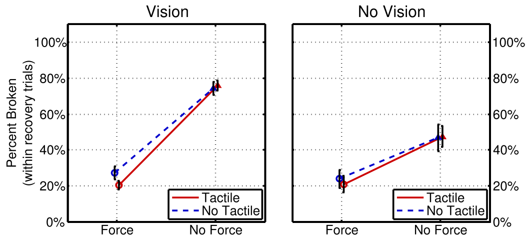

Fig. 7: *% broken* within each feedback condition across subjects ($n = 22$, outlier removed) within recovery trials. Error bars represent standard error across subjects within each feedback condition. Force feedback reduces the percentage of trials in which subjects break the object. Tactile feedback has no effect on subjects' likelihood of breaking the object, even in recovery trials.

3.6 Mean Force

There was a significant main effect of feedback condition on the mean force applied by the user to the object ($F(7,147) = 19.11$, $p < 0.029$ (G-G), $\eta^2_{partial} = 0.474$). A figure of the mean forces within each feedback condition, and table of means, standard deviations, and effect sizes are given in the Appendix. The pairwise comparisons show that subjects applied lower forces on average when force feedback was available. Tactile feedback had no noticeable effect on subjects' applied forces. The complex contrasts show a significant difference between the force and no-force feedback for the no vision conditions ($t(147) = 9.939$, $p < 0.001$), where the force feedback (vF) yielded lower force than the no-force (vf) conditions.

3.7 Percent Broken

Figure 7 considers only those trials in which the object slipped and was recovered, showing the percentage of such trials in

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which the object was broken, with Table 2 showing significant pairwise comparisons (see ‡). There was a significant main effect of feedback condition ($F(7,147) = 29.19,\ p < 0.001$ (G-G), $\eta^2_{partial} = 0.582$). Force feedback reduced the *% broken*, and tactile feedback had no effect, suggesting that the improvements in *% recovery* due to tactile feedback did not result in a corresponding increase in object breaking. The complex contrasts showed that the vision conditions had a larger *% broken* than the no vision conditions ($t(147) = 4.887$, $p < 0.001$) and the no vision force (vF) conditions had a significantly smaller *% broken* than the no vision no force (vf) conditions ($t(147) = 5.828,\ p < 0.001$).

Similar to the within-recovery results, overall force feedback reduces the percentage of trials in which subjects break the object. Tactile feedback has no effect on subjects' likelihood of breaking the object. In the complex contrasts, the vision conditions had a significantly larger *% broken* than the no vision conditions ($t(147) = 4.374,\ p < 0.001$), and the no vision force (vF) conditions had a significantly smaller *% broken* than the no vision no force (vf) conditions ($t(147) = 9.993,\ p < 0.001$). Given in the Appendix is a figure and table showing means, standard deviations, and effect sizes of the percentage of all trials in which the object was broken. There was a significant main effect of feedback condition ($F(7,147) = 54.37,\ p < 0.001$ (G-G), $\eta^2_{partial} = 0.721$).

3.8 Summary

As expected, we found an overall strong influence of vision on performance. We found that in the absence of vision, tactile feedback improves performance especially under the transition conditions. In the presence of vision, the only performance metric improved by tactile feedback is *% time slipping*. The presentation of force feedback resulted in equivocal results: 1) beneficial effects in *% recovery* in the heavy-light transition over the no feedback condition and 2) deleterious effects overall with an increase in the number of slips and more time spent slipping. Force feedback reduced subjects' applied force and likelihood of breaking the object. Tactile feedback had no effect on applied force or subjects' likelihood to break the object (both overall and within only trials in which the object slipped and was recovered). Taken together, we found that sensory feedback modalities of vision, vibratory tactile and force feedback had different influences on performance. If vision is available, most users will use visual information to guide task performance. However, if there is no vision information available, then vibratory tactile information is a useful alternative sensory feedback modality to enhance performance in responding to object slippage. See the Appendix for a summary table of the results.

4 DISCUSSION

We explored the value of providing slip information via vibrotactile feedback to the upper arm in a virtual grasp and hold task. When grasping an object, a healthy individual senses object slip with cutaneous information from the fingertips. Both skin stretch and tactile vibrations alert an individual to slip, and he or she instinctively adjusts the force on the object [8]. However, an amputee using a conventional myoelectric prosthetic hand has no way to sense slip or pass this information to the central nervous system. Therefore, prosthesis users tend to rely heavily on vision when manipulating objects. By carefully watching a grasped object, they can see slip occurring and adjust grip force in response. We believe that substituting that cutaneous slip sensation with a vibrotactile cue to the residual limb will improve the ease with which a prosthesis user could adjust grasp to avoid slip, improving dexterity.

Vibrotactile cues are commonly used to provide haptic information to users non-invasively. Others have used these cues to encode grip force in a similar grasping task [21], [22]. In contrast, we applied vibration corresponding to object slip, exploring the hypothesis that this additional information could improve a participant's ability to adjust grip force and prevent an object from slipping out of grasp. The virtual task was a simplified way to explore grasping and response to slip. By changing feedback conditions, and by changing the weight and breaking-threshold of the object within feedback conditions, we were able to explore how tactile feedback affects grasping in changing force and vision situations and with constant or unpredictable object properties.

Information on the feedback conditions, object's position, the force applied against the object was analyzed from the virtual task under different feedback conditions. We investigated trends in slip response for each combination of visual, tactile, and force feedback. The percentage of slips recovered, the amount of time that the object spent slipping, and the percentage of slips to which users responded varied across feedback conditions and after object weight changes.

4.1 Percentage of Slips Recovered

Our primary interest is the value of tactile feedback for conveying slip information and enabling subjects to respond in a manner that would be useful in a real task, i.e., stopping a slipping object before it is dropped, illustrated by *% recovery*.

4.1.1 Percent Recovery Overall

First, we consider the overall effect of feedback on *% recovery*, regardless of object weight. When visual feedback was available, subjects were able to recover almost all slipping objects, illustrated by the high recovery rates over 90%. This situation is analogous to a prosthesis user visually monitoring his or her gripper while interacting with an object. In this case, we saw no significant improvements due to haptic feedback. However, we are interested in enabling users to interact with objects without needing to carefully watch the gripper. With currently available prosthetic limbs, this scenario would correspond to the no feedback case (vft) in our experiment, where we see a fairly low recovery rate of 42%. The potential of haptic feedback to improve interaction with objects is illustrated by the significant increase in *% recovery* with tactile feedback with a very large effect size (vfT vs. vft in Table 3, see Appendix). Tactile feedback clearly improves subjects' ability to recover a slipping object, with an increase in *% recovery* to 80%. A similar improvement due to tactile feedback is seen when force feedback is available in the no vision conditions:

% recovery significantly increases with a large effect size, from 39% to 66%. These findings clearly demonstrate the potential for tactile feedback of slip information to improve users' ability to grasp objects without dropping them.

We are also interested in how the availability of force feedback impacts users' ability to recover a slipping object and whether force feedback changes the effectiveness of tactile feedback. We saw in our preliminary analysis that more slips occurred when force feedback was available in the no vision conditions [31]. Without force feedback, subjects had more difficulty regulating their forces precisely and tended to apply excessive force to the object, as has been similarly observed in physical grasping tasks [39]. This results in more breaking of the object and less slipping. This tendency can also account for the lower *% recovery* observed with force feedback. When force feedback is not available, subjects are more likely to overcompensate for slip with excessive force. In contrast, with force feedback, subjects can respond with a more carefully controlled force; in this case, subjects often tried to stop slip with the smallest amount of force possible, which sometimes resulted in a failure to recover the slipping object. Such errors may be corrected with more practice and extended use of the system, and we plan to explore this possibility in future work.

Another consideration in the effect of force feedback is the application method. Force feedback is applied via the Phantom, which is also used for the control input. Thus, when force feedback is available, the subject encounters some resistance in increasing the applied forces on the object and must therefore make more effort to generate the same amount of force in a force feedback condition than in a no force feedback condition. This interference between force feedback and the control input would also tend to reduce the forces applied by the user and result in more difficulty recovering a slipping object. The degree of interference in a real prosthesis system will clearly depend on the feedback method used. If force feedback is applied via a joint torque (e.g., [21]) and control is implemented via EMG, then some interference is likely. However, if force feedback is applied via a vibrotactile system instead, then interference is less likely. Using the Phantom and a virtual environment enabled easy changes to the experiment design and precise data collection. Because this virtual experiment indicates that vibrotactile slip feedback would improve recovery of slips in object manipulation, we now plan to explore this in a physical system with alternate methods to relay force feedback, which would more closely align with a real prosthesis.

4.1.2 Percent Recovery After Weight Changes

Often when interacting with objects in our environment, we pick up objects that are heavier or lighter than we expect or have unexpected mechanical properties. In such cases, haptic feedback allows able-bodied individuals to adjust their applied forces to compensate for unexpected differences in the object's weight or material properties. We explored the importance of tactile and force feedback in such conditions by changing the weight and breaking force threshold of the virtual object.

Light-to-heavy transitions were used to induce slip due to the unexpected increase in required grip force. These trials showed the same trends in effects of vision and tactile feedback as were seen in the overall analysis of *% recovery*: haptic feedback has strong effects when visual feedback is not available, and tactile feedback significantly improves *% recovery* without visual feedback regardless of the availability of force feedback. The effect of force feedback is more pronounced in these transition trials with a larger decrease in *% recovery* when force feedback is available. This effect again highlights the manner in which subjects use force feedback to interact with the virtual object. When force feedback is not available, subjects are likely to overcompensate for slip when the object weight has not changed; this tendency would make them more likely to recover the object when it is heavier than expected because they are applying higher forces than they would be expected to need. When force feedback is available, subjects are able to regulate their forces more precisely, so they would need more time to notice that the force increase is insufficient for the new object weight and to compensate appropriately. Subjects must also overcome a larger feedback force in order to command the necessary increase in the force on the object, slowing down their response.

Heavy-to-light transitions serve to change the breaking threshold of the object unexpectedly, again causing subjects to change the applied force during the trial. These trials also showed the same overall trends in effects of vision and tactile feedback, but different trends in the effect of force feedback under no vision conditions. In the no vision, no tactile cases, force feedback actually improved *% recovery* after the heavy-to-light transitions. In this case, it is possible that subjects were applying force levels learned from the heavy object, which would easily recover the light object from slipping. We also note that *% recovery* was slightly higher in heavy-to-light transitions than in the light-to-heavy transitions for all feedback conditions, likely due to the smaller forces required to stop the object from slipping.

4.2 Percentage of Time Slipping

For another perspective on subjects' ability to grasp objects, we consider the percentage of time that the object was slipping. A larger *% time slipping* corresponds to more slips, fewer recoveries, or a longer time needed to recover the slipping object. This metric is practically relevant because a slipping object requires more attention than one that is securely grasped, so we would like users to experience fewer slips and recover from slips more often and more quickly.

4.2.1 Percent Time Slipping Overall

Subjects experienced more time slipping when visual feedback was not available, again highlighting the importance of alternate forms of feedback. Tactile feedback significantly decreased *% time slipping* when vision was not available, almost to the levels that subjects were able to achieve with vision under equivalent force feedback conditions. Force feedback increased the *% time slipping*, consistent with our observation that subjects were less likely to recover a slipping object with force feedback. Again, this effect is likely due to a combination of the ability to control forces more precisely with force feedback and the tendency of force feedback to slow down a user's control input response.

4.2.2 Percent Time Slipping after Weight Changes

After light-to-heavy object transitions, there were clearer effects of feedback on *% time slipping*. Visual feedback tended to reduce *% time slipping*, as did tactile feedback. In contrast, force feedback tended to increase *% time slipping*. These results are mostly consistent with the effects of feedback on *% recovery*. Visual feedback and tactile feedback allow users to detect and respond to slip, decreasing the amount of time the object is slipping. Force feedback slows down the response to slip, increasing in the amount of time slipping. Notably, in this metric there is an improvement due to tactile feedback even when visual feedback is available, indicating that when a grasped object is heavier than expected, the extra cue due to tactile feedback might help a prosthesis user reduce slip even when the user is watching the gripper.

After heavy-to-light object transitions, no significant effects on *% time slipping* were found due to feedback conditions. This lack of effect may be due to an overall reduced tendency towards slip, since subjects were more likely to overestimate the necessary force to grasp the object.

4.3 Response to Slip

The *% response to slip* gives an indication of how easily subjects were able to detect and respond to slip, regardless of whether they were actually able to stop slip in time to recover the object. Subjects were extremely likely to respond to slip when visual feedback was available, but less likely without visual feedback. Without vision, tactile feedback made subjects much more likely to respond to slip before the end of the trial, though slightly less likely than with vision. There was not a significant difference in *% response to slip* when the weight of the object changed. Force feedback had no effect on whether subjects responded to slip or not. These results indicate a clear benefit of tactile feedback in helping a user to detect object slip non-visually.

The finding that force feedback has no effect on subjects' likelihood to respond to slip is also significant. Though force feedback is useful in reducing grasp forces and preventing damage to a grasped object [21], it is not effective at reducing slips or communicating the occurrence of a slip to a user. When force feedback is incorporated into a device, users are more likely to exert smaller forces close to the slip threshold. Thus, the role of tactile feedback is even more important when force feedback is in use, to mitigate the effect of increased slip.

4.4 Applied Force and Object Breaking

This grasp and hold study focused mainly on the adjustment of grasp forces to respond to object slip; however, maintaining a grasp force low enough to prevent breaking the object was a major component of this task and of object manipulation with real prostheses. Previous studies [39] have shown that grip force feedback for prosthetic hands significantly reduces the frequency of object damage. We saw the same trend in this study. When the participant was provided force feedback, the *mean force* on the object was lower than without force feedback (1.24 N compared to 1.68 N), and the percentage of objects broken was lower (25% compared to 70%). There was no significant change in *% breaks* with and without tactile feedback. Within the trials where objects were recovered, tactile feedback did not affect the percentage of objects broken. It improves users' abilities to recover slipping objects without negatively affecting the forces users applied to the object.

In the no vision case, when force feedback was applied, although there were fewer breaks, there were also more slips. Because users were more aware of the force they were applying, they applied lower force, and therefore were more likely to drop below the minimum force required to keep the object from slipping. For this reason, it is especially valuable to have tactile slip feedback when force feedback is applied. Slip feedback alerts the subject when the force is too low and the object might be dropped. In this way, one can modulate the force to be in a safe range between breaking and dropping thresholds. Force feedback helps prevent too-high forces, and tactile feedback can help prevent too-low forces.

5 CONCLUSION

In this study, we examined the importance of vibratory tactile feedback of slip information in combinations with visual and/or force feedback in a virtual grasp and hold task. Our primary interest in this study was to determine the extent to which vibratory tactile feedback of slip information can aid users in this grasp and hold task in the absence of visual feedback, with the overall goal of enabling prosthesis users to interact with objects without needing to pay careful visual attention to the gripper interactions. Results showed that tactile feedback improved users' ability to detect and respond to slip without visual feedback, as well as their ability to recover a slipping object before dropping it, indicating that this feedback method may aid users of advanced prostheses in grasping tasks. Tactile feedback is especially important in conjunction with force feedback; because force feedback encourages the use of lower grasping forces, users are more likely to experience slip, and therefore more likely to make use of the tactile feedback in recovery from slip.

In the future, we plan to incorporate this feedback into a physical system to test grasping of real objects. This system will include EMG control to test the practicality of the feedback in conjunction with a realistic control method and ensure that the feedback does not interfere with the control. We will also explore the importance of incipient slip feedback in reducing the occurrence of slip and users' ability to learn the proper grip forces to apply to different objects. We are also currently exploring the level of mental effort associated with the different feedback methods. Studying these factors will provide further insight into how to best integrate slip feedback with other forms of feedback for advanced prosthesis systems.

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REFERENCES

[1] E. Guizzo, "Dean Kamen's "Luke Arm" prosthesis receives FDA approval," *IEEE Spectrum*, May 2014. [Online]. Available: http://spectrum.ieee.org/automaton/biomedical/bionics/dean-kamen-luke-arm-prosthesis-receives-fda-approval/

[2] D. J. Atkins, D. C. Y. Heard, and W. H. Donovan, "Epidemiologic overview of individuals with upper-limb loss and their reported research priorities," *J. Prosthetics and Orthotics*, vol. 8, no. 1, pp. 2–11, 1996.

[3] H. Ayaz, S. Bunce, P. A. Shewokis, K. Izzetoglu, B. Willems, and B. Onaral, "Using brain activity to predict task performance and operator efficiency," in *Proc. Int. Conf. and Symp. on Brain Inspired Cognitive Systems*, 2012, pp. 147–155.

[4] L. Panait, S. Shetty, P. A. Shewokis, and J. A. Sanchez, "Do laparoscopic skills transfer to robotic surgery?" *J. Surg. Res.*, vol. 187, no. 1, pp. 53–58, 2014.

[5] J. Gonzalez, H. Soma, M. Sekine, and W. Yu, "Psycho-physiological assessment of a prosthetic hand sensory feedback system based on an auditory display: A preliminary study," *J. Neuroeng. and Rehab.*, vol. 9, no. 1, p. 33, 2012.

[6] J. R. Flanagan and A. M. Wing, "The role of internal models in motion planning and control: Evidence from grip force adjustments during movements of hand-held loads," *J. Neurosci.*, vol. 17, no. 4, pp. 1519–1528, Feb 1997.

[7] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks," *Nat. Rev. Neuroscience*, vol. 10, no. 5, pp. 345–359, 2009.

[8] M. Wiertlewski, S. Endo, A. M. Wing, and V. Hayward, "Slip induced vibration influences the grip reflex," *Proc. World Haptics Conf.*, pp. 627–632, 2013.

[9] D. A. Nowak and J. Hermsdoerfer, "Selective deficits of grip force control during object manipulation in patients with reduced sensibility of the grasping digits," *Neuroscience Research*, vol. 47, pp. 65–72, May 2003.

[10] D. A. Nowak, J. Hermsdoerfer, S. Glasauer, J. Philipp, L. Meyer, and N. Mai, "The effects of digital anaesthesia on predictive grip force adjustments during vertical movements of a grasped object," *European Journal of Neuroscience*, vol. 14, pp. 756–762, 2001.

[11] W. Zhang, A. M. Gordon, T. L. McIsaac, and M. Santello, "Within-trial modulation of multi-digit forces to friction," *Exp Brain Res*, vol. 211, pp. 17–26, April 2011.

[12] D. Kourtis, H. F. Kwok, N. Roach, A. M. Wing, and P. Praamstra, "Maintaining grip: Anticipatory and reactive EEG responses to load perturbations," *J Neurophysiol*, vol. 99, pp. 545–553, November 2007.

[13] N. Masataka, M. Konyo, T. Maeno, and S. Tadokoro, "Reflective grasp force control of humans induced by distributed vibration stimuli on finger skin with ICPF actuators," in *Proc. IEEE Int. Conf. on Robotics and Automation, 2006*, 2006, pp. 3899–3904.

[14] J. Ueda, A. Ikeda, and T. Ogasawara, "Grip-force control of an elastic object by vision-based slip-margin feedback during the incipient slip," *IEEE Trans. on Robotics*, vol. 21, no. 6, pp. 1139–1147, 2005.

[15] I. Saunders and S. Vijayakumar, "The role of feed-forward and feedback processes for closed-loop prosthesis control," *J NeuroEng and Rehab*, vol. 8, no. 60, 2011.

[16] C. Cipriani, F. Zaccone, S. Micera, and M. C. Carrozza, "On the shared control of an EMG-controlled prosthetic hand: Analysis of user-prosthesis interaction," *IEEE Trans. on Robotics*, vol. 24, no. 1, pp. 170–184, 2008.

[17] S. Raspopovic, M. Capogrosso, F. M. Petrini, M. Bonizzato, J. Rigosa, G. Di Pino, J. Carpaneto, M. Controzzi, T. Boretius, E. Fernandez *et al.*, "Restoring natural sensory feedback in real-time bidirectional hand prostheses," *Sci Transl Med*, vol. 6, no. 222, p. 222ra19, Feb 2014.

[18] K. Bark, J. Wheeler, G. Lee, J. Savall, and M. Cutkosky, "A wearable skin stretch device for haptic feedback," in *Proc. Joint Eurohaptics Conf. and Haptics Symp.*, 2009, pp. 464–469.

[19] K. A. Kaczmarek, "Sensory augmentation and substitution," in *CRC Handbook of Biomed. Eng.*, J. D. Bronzino, Ed. Boca Raton, FL: CRC Press LLC, 2000, pp. 143.1–143.10.

[20] C. Antfolk, A. Björkman, S.-O. Frank, F. Sebelius, G. Lundborg, and B. Rosen, "Sensory feedback from a prosthetic hand based on air mediated pressure from the hand to the forearm skin," *J Rehabil Med*, vol. 44, pp. 702–707, 2012.

[21] J. D. Brown, A. Paek, M. Syed, M. K. O'Malley, P. Shewokis, J. L. Contreras-Vidal, and R. B. Gillespie, "Understanding the role of haptic feedback in a teleoperated/prosthetic grasp and lift task," in *Proc. Haptics Symp.*, 2013, pp. 271–276.

[22] M. D'Alonzo, C. Cipriani, and M. C. Carrozza, "Vibrotactile sensory substitution in multi-fingered hand prostheses: Evaluation studies," in *Proc. IEEE Int. Conf. on Rehab. Robotics*, 2011, pp. 1–6.

[23] C. Antfolk, M. D'Alonzo, M. Controzzi, G. Lundborg, B. Rosen, F. Sebelius, and C. Cipriani, "Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: vibrotactile versus mechanotactile sensory feedback," *IEEE Trans. Neural Systems and Rehab. Eng.*, vol. 21, no. 1, pp. 112–120, 2013.

[24] A. Ajoudani, S. B. Godfrey, M. Bianchi, M. G. Catalano, G. Grigoli, N. Tsagarakis, and A. Bicchi, "Exploring teleimpedance and tactile feedback for intuitive control of the pisa/iit softhand," *IEEE Trans. Haptics*, vol. 7, no. 2, pp. 203–15, Apr-June 2014.

[25] H. J. B. Witteveen, L. de Rond, J. S. Rietman, and P. H. Veltink, "Hand-opening feedback for myoelectric forearm prostheses: Performance in virtual grasping tasks influenced by different levels of distraction," *JRRD*, vol. 49, no. 10, pp. 1517–1526, 2012.

[26] D. D. Damian, A. H. Arieta, H. Martinez, and R. Pfeifer, "Slip speed feedback for grip force control," *IEEE Trans. on Biomedical Engineering*, vol. 59, no. 8, pp. 2200–2210, August 2012.

[27] E. P. W. Van der Putten, J. J. van den Dobbelsteen, R. H. M. Goossens, J. J. Jakimowicz, and J. Dankelman, "The effect of augmented feedback on grasp force in laparoscopic grasp control," *IEEE Trans. Haptics*, vol. 3, no. 4, pp. 280–291, 2010.

[28] K. Kim and J. Colgate, "Haptic feedback enhances grip force control of semg-controlled prosthetic hands in targeted reinnervation amputees," *IEEE Trans. Neural Sys. and Rehab. Eng.*, vol. 20, no. 6, pp. 798–805, Nov 2012.

[29] R. Christiansen, J. L. Contreras-Vidal, , R. B. Gillespie, P. Shewokis, and M. K. O'Malley, "Vibrotactile feedback of pose error enhances myoelectric control of a prosthetic hand," in *Proc. Haptics Symp.*, 2013, pp. 531–536.

[30] F. Sergi, D. Accoto, D. Campolo, and E. Guglielmelli, "Forearm orientation guidance with a vibrotactile feedback bracelet: On the directionality of tactile motor communication," in *Proc. IEEE Int. Conf. on Biomed. Robotics and Biomechatronics*, 2008, pp. 433–438.

[31] J. M. Walker, A. A. Blank, P. A. Shewokis, and M. K. O'Malley, "Tactile feedback of object slip improves performance in a grasp and hold task," in *Proc. IEEE Haptics Symposium*, 2014, pp. 461–466.

[32] L. Skedung, K. Danerlöv, U. Olofsson, M. Aikala, K. Niemi, J. Kettle, and M. W. Rutland, "Finger friction measurements on coated and uncoated printing papers," *Tribology Letters*, vol. 37, no. 2, pp. 389–399, 2010.

[33] L. Skedung, K. Danerlöv, U. Olofsson, C. Michael Johannesson, M. Aikala, J. Kettle, M. Arvidsson, B. Berglund, and M. W. Rutland, "Tactile perception: finger friction, surface roughness and perceived coarseness," *Tribology International*, vol. 44, no. 5, pp. 505–512, 2011.

[34] R. Lewis, C. Menardi, A. Yoxall, and J. Langley, "Finger friction: grip and opening packaging," *Wear*, vol. 263, no. 7, pp. 1124–1132, 2007.

[35] A. Kargov, C. Pylatiuk, J. Martin, S. Schulz, and L. Döderlein, "A comparison of the grip force distribution in natural hands and in prosthetic hands," *Disability & Rehab*, vol. 26, no. 12, pp. 705–711, 2004.

[36] J. Dosher and B. Hannaford, "Human interaction with small haptic effects," *Presence*, vol. 14, no. 3, pp. 329–344, June 2005.

[37] R. J. A. Little and D. B. Rubin, *Statistical Analysis with Missing Data*. New York: Wiley & Sons, 1987.

[38] Y. Benjamini and Y. Hochberg, "Controlling the false discovery rate: A practical and powerful approach to multiple testing," *J. Royal Statistical Society. Series B (Methodological)*, pp. 289–300, 1995.

[39] D. A. Nowak, S. Glasauer, and J. Hermsdorfer, "How predictive is grip force control in the complete absense of somatosensory feedback?" *Brain*, vol. 127, pp. 182–192, Jan 2004.

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APPENDIX
DESCRIPTIVE STATISTICS AND EFFECT SIZES

The following tables provide effect sizes for all pairwise comparisons described in Section 3. Effect sizes were calculated using the row condition minus the column condition, so a negative effect size indicates that the feedback condition listed in the row heading has a smaller mean. (For example, in Table 6, the negative effect size of -0.053 in the first cell indicates that the mean in the VFT condition is smaller than the mean in the VFt condition.)

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.949	0.080	0.333	-0.101	-0.099	1.502*	2.969*	0.933	2.809*
VFt	0.916	0.115		-0.441	-0.251	1.277*	2.667*	0.678	2.514*
VfT	0.956	0.057			0.214	1.571*	3.076*	1.010*	2.912*
Vft	0.941	0.081				1.460*	2.923*	0.881	2.763*
vFT	0.656	0.264					1.021*	-0.614	0.905*
vFt	0.392	0.253						-1.770*	-0.119
vfT	0.802	0.208							1.641*
vft	0.422	0.253							

🟨	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 3
Descriptive statistics and Cohen's d effect sizes for all paired comparisons for *% recovery*. * indicates a significant pairwise comparison at a family-wise α level of 0.05.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.857	0.309	0.271	-0.173	-0.288	1.447*	2.326*	0.081	1.003*
VFt	0.765	0.368		-0.452	-0.572	1.103*	1.834*	-0.207	0.690
VfT	0.904	0.232			-0.119	1.722*	2.797*	0.274	1.238*
Vft	0.927	0.165				1.919*	3.185*	0.409	1.402*
vFT	0.341	0.400					0.555	-1.418*	-0.398
vFt	0.143	0.307						-2.333*	-1.003*
vfT	0.833	0.284							0.962
vft	0.500	0.399							

🟨	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 4
Descriptive statistics and Cohen's d effect sizes for all paired comparisons for *% recovery* after light-to-heavy object transitions. * indicates a significant pairwise comparison at a family-wise α level of 0.05.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	1.000	0.000	0.000	0.000	0.760	1.309	1.585*	0.854	2.783*
VFt	1.000	0.000		0.000	0.760	1.309	1.585*	0.854	2.783*
VfT	1.000	0.000			0.760	1.309	1.585*	0.854	2.783*
Vft	0.932	0.179				0.577	0.822	0.236	1.655*
vFT	0.786	0.327					0.229	-0.296	0.899*
vFt	0.706	0.371						-0.519	0.634*
vfT	0.877	0.288							1.222*
vft	0.467	0.383							

🟨	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 5
Descriptive statistics and Cohen's d effect sizes for all paired comparisons for *% recovery* after heavy-to-light object transitions. * indicates a significant pairwise comparison at a family-wise α level of 0.05.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.295	0.167	-0.053	1.012*	0.678	-0.262	-0.763*	0.949*	0.103
VFt	0.304	0.174		1.056*	0.732	-0.215	-0.712*	0.989*	0.157
VfT	0.171	0.078			-0.573	-1.102*	-1.643*	0.055	-0.969
Vft	0.214	0.072				-0.852*	-1.428*	0.542	-0.599
vFT	0.349	0.245					-0.445	1.046*	0.359
vFt	0.466	0.281						1.554*	0.878*
vfT	0.166	0.105							-0.904
vft	0.279	0.145							

🟨	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 6
Descriptive statistics and Cohen's d effect sizes for all paired comparisons for *% time slipping* under each feedback condition. * indicates a significant pairwise comparison at a family-wise α level of 0.05.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.413	0.261	-0.338	0.994	0.625	-0.705	-0.903*	0.838	0.217
VFt	0.510	0.309		1.268*	0.949*	-0.374	-0.564	1.107*	0.483
VfT	0.196	0.166			-0.550	-1.561*	-1.774*	-0.021	-0.498
Vft	0.281	0.145				-1.285*	-1.505*	0.400	-0.212
vFT	0.636	0.363					-0.178	1.404*	0.789*
vFt	0.701	0.367						1.600	0.958
vfT	0.200	0.247							-0.442
vft	0.343	0.382							

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 7

Descriptive statistics and Cohen's d effect sizes for all paired comparisons for *% time slipping* after light-to-heavy object transitions. * indicates a significant pairwise comparison at a family-wise α level of 0.05.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.224	0.236	0.417	0.493	0.017	0.322	-0.211	0.036	-0.098
VFt	0.139	0.168		0.035	-0.516	-0.049	-0.538	-0.394	-0.439
VfT	0.134	0.106			-0.670	-0.081	-0.590	-0.474	-0.490
Vft	0.221	0.149				0.368	-0.246	0.026	-0.123
vFT	0.149	0.233					-0.464	-0.296	-0.366
vFt	0.287	0.351						0.243	0.105
vfT	0.216	0.220							-0.129
vft	0.252	0.322							

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 8

Descriptive statistics and Cohen's d effect sizes for *% time slipping* after heavy-to-light object transitions. Since the one-way repeated measures ANOVA found no significant difference, pairwise comparisons were not conducted.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.946	0.072	-0.530	0.097	-0.091	0.794	1.487*	0.621	1.514*
VFt	0.976	0.035		0.546	0.369	1.058*	1.676*	0.861	1.694*
VfT	0.938	0.092			-0.173	0.709	1.420*	0.548	1.450*
Vft	0.953	0.081				0.829	1.509*	0.658	1.536*
vFT	0.833	0.188					0.796*	-0.103	0.849*
vFt	0.644	0.278						-0.865*	0.067
vfT	0.853	0.199							0.915*
vft	0.625	0.291							

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 9

Descriptive statistics and Cohen's d effect sizes for all paired comparisons for *% response to slip* under each feedback condition. * indicates a significant pairwise comparison at a family-wise α level of 0.05.

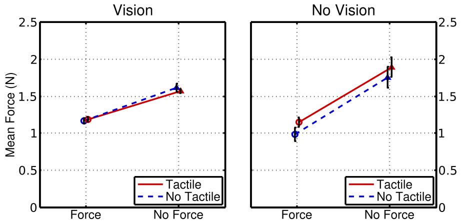

Fig. 8: *Mean force* within each feedback condition across subjects ($n = 22$, outlier removed). Error bars represent standard error across subjects within each feedback condition. Subjects applied lower forces on average when force feedback was available. Tactile feedback had no noticeable effect on subjects' applied forces.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	1.188	0.155	0.117	-2.588*	-2.109*	0.175	0.703	-1.771*	-1.365*
VFt	1.168	0.186		-2.465*	-2.050*	0.084	0.601	-1.753*	-1.362*
VfT	1.571	0.141			-0.225	1.868*	2.086*	-0.822	-0.450
Vft	1.615	0.250				1.663*	1.878*	-0.622	-0.302
vFT	1.147	0.313					0.439	-1.563*	-1.230*
vFt	0.986	0.420						-1.709*	-1.403*
vfT	1.892	0.640							0.208
vft	1.755	0.676							

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 10

Descriptive statistics for mean force within each feedback condition ($n = 22$, outlier removed). * indicates a significant pairwise comparison at a family-wise α level of 0.05.

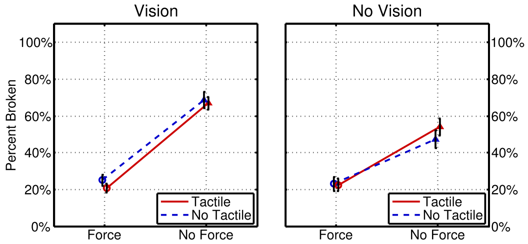

Fig. 9: Percent of trials in which the object was broken within each feedback condition across subjects ($n = 22$, outlier removed) over all trials. Error bars represent standard error across subjects within each feedback condition. Force feedback reduces the percentage of trials in which subjects break the object. Tactile feedback has no effect on subjects' likelihood of breaking the object.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.208	0.121	-0.336	-3.293*	-2.906*	-0.119	-0.150	-1.903*	-1.497*
VFt	0.252	0.141		-2.780*	-2.487*	0.177	0.128	-1.561*	-1.182*
VfT	0.669	0.159			-0.093	2.749*	2.539*	0.667*	1.000*
Vft	0.686	0.208				2.478*	2.310*	0.670*	0.966*
vFT	0.225	0.164					-0.034	-1.607*	-1.249*
vFt	0.231	0.186						-1.493*	-1.155*
vfT	0.540	0.228							0.291
vft	0.473	0.233							

🟨	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 11
Descriptive statistics for *% broken* within each feedback condition across all trials ($n = 22$, outlier removed). * indicates a significant pairwise comparison at a family-wise α level of 0.05.

Feedback Group	*Mean*	*SD*	*Effect Size*						
			VFt	VfT	Vft	vFT	vFt	vfT	vft
VFT	0.204	0.116	-0.483	-4.531*	-3.729*	-0.030	-0.199	-1.371*	-1.102*
VFt	0.273	0.170		-3.251*	-2.737*	0.327	0.168	-0.897*	-0.732*
VfT	0.759	0.129			0.120	3.134*	2.857*	1.400*	1.183*
Vft	0.741	0.172				2.701*	2.467*	1.187*	1.021*
vFT	0.209	0.222					-0.131	-1.060*	-0.885*
vFt	0.239	0.235						-0.916*	-0.766*
vfT	0.474	0.278							0.019
vft	0.468	0.363							

🟨	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 12
Descriptive statistics for *% broken* in recovery trials within each feedback condition ($n = 22$, outlier removed). * indicates a significant pairwise comparison at a family-wise α level of 0.05.

Performance Metric	*Condition*	*Effects of Vision*	*Effects of Force Feedback*	*Effects of Tactile Feedback*
Number of Slips [31]	Overall	More slips with visual feedback	More slips with force feedback	No effect
% Recovery	Overall	Fewer recoveries without visual feedback	In no-vision condition, fewer recoveries with force feedback	In no-vision condition, more recoveries with tactile feedback
% Recovery	After light-to-heavy transition	Fewer recoveries without visual feedback, in most haptic feedback cases	In no-vision condition, fewer recoveries with force feedback	In no-vision condition, more recoveries with tactile feedback than with no feedback
% Recovery	After heavy-to-light transition	Fewer recoveries without visual feedback, when tactile feedback is not available	In no-vision condition, more recoveries with force feedback than with no feedback	In no-vision condition, more recoveries with tactile feedback than with no feedback
% Time Slipping	Overall	More time slipping without visual feedback, except compared to no feedback	In no-vision condition, more time slipping with force feedback	In no-vision condition, more time slipping without tactile feedback
% Time Slipping	After light-to-heavy transition	More time slipping without visual feedback	More time slipping with force feedback	More time slipping without tactile feedback
% Time Slipping	After heavy-to-light transition	No effect	No effect	No effect
% Response to Slip	Overall	More response to slip with visual feedback	No effect	In no-vision condition, more response to slip with tactile feedback
Mean Force	Overall	No effect	Lower mean force with force feedback	No effect
% Broken	Overall	Larger *% broken* with visual feedback in no-force condition	Lower *% broken* with force feedback	No effect
% Broken	Within recovery trials	Larger *% broken* with visual feedback in no-force condition	Lower *% broken* with force feedback	No effect

TABLE 13
Summary of performance metrics and significant effects of feedback conditions.