Towards an Understanding of the Utility of Dual-Modality Haptic Feedback in Teleoperated Medical Devices

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***Abstract*—Humans normally integrate multiple haptic signals during dexterous manipulation with the natural limb. Operating telerobots such as surgical robots and upper-limb prostheses removes this multimodality feedback. While considerable research has focused on single-modality haptic feedback and discrete multimodality haptic feedback, little is known regarding the utility of continuous multimodality feedback. Here, we present an experimental framework designed to explore continuous multimodality haptic feedback for dexterous manipulation. Participants performed a grasp-and-hold task in a virtual environment with either direct or myoelectric control under different haptic feedback conditions: no feedback, vibrotactile feedback of object slip, squeeze feedback of grip force, and combined vibrotactile and squeeze feedback. Results from preliminary pilot studies highlight the gap in knowledge surrounding the potential utility of continuous multimodality feedback in differing telerobot control scenarios.**

***Index Terms*—Haptic feedback, teleoperation, multimodality, robotic surgery, prosthetics.**

I. Introduction

Humans are endowed with a remarkable capacity for dexterous manipulation. From simple tasks like drinking a cup of coffee and tying one's shoes to more complicated tasks like suturing, success depends on the ability to integrate multiple tactile cues such as grip force and incipient slip. Yet, at present, the majority of haptic interfaces proposed for teleoperated medical devices such as telesurgical robots and upper-limb myoelectric prostheses are capable of providing only one type of tactile cue. These single-modality haptic displays force the operator to rely more heavily on visual feedback to infer task-related information [1], which has been associated with high cognitive demand [2].

Recent efforts focused on investigating multimodality feedback for telerobotic applications have begun to demonstrate the potential utility of these interfaces for basic object manipulation tasks [1], [3], [4]. However, some work has found multimodality feedback to be less helpful than single-modality feedback in areas of task performance [5] and perception [6], [7], indicating that further investigation is needed. Additionally, these efforts have largely focused on perception, event-based haptic cues, and task objects with fixed properties [4], [8]. In both surgical and prosthetic domains, the object being grasped may experience changes in load, as is the case with pulling a suture or shoestring tight. Likewise, excessive grip force may have unwanted consequences such as damaging tissue or breaking brittle objects. Thus, the grip force required to complete a task may need to be continuously varied rather than discretely fixed.

Here, we present an experimental framework designed to investigate the utility of continuous dual-modality haptic feedback for dexterous manipulation with teleoperated medical devices. Utilizing a virtual grasp-and-hold task with brittle objects of variable load, we can independently assess the role of slip feedback and grip force feedback with both direct and myoelectric control interfaces. In what follows, we describe our experimental setup as well as the protocols and results from two pilot studies.

Manuscript received July 15, 2020; revised October 10, 2020; accepted October 21, 2020. Date of publication October 27, 2020; date of current version November 20, 2020. This article was recommended for publication by Associate Editor F. Rodriguez y Baena and Editor P. Dario upon evaluation of the reviewers' comments. This work was supported by internal Johns Hopkins funds. *(Sergio Machaca and Garrett Ung contributed equally to this work.) (Corresponding author: Garrett Ung.)*

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Digital Object Identifier 10.1109/TMRB.2020.3034254

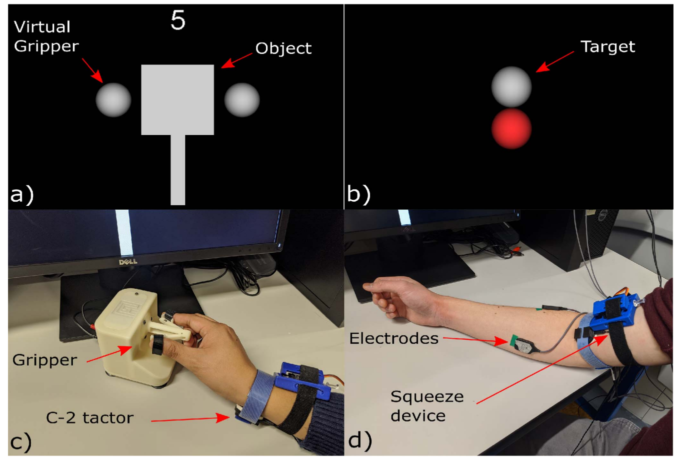

Fig. 1. a) Experimental grasp-and-hold task virtual environment showing the object and grippers b) Position-tracking EMG practice task virtual environment c) Direct control interface d) Myoelectric control interface.

II. General Materials and Methods

A. Experimental Setup

The experimental setup consisted of two control interfaces, a virtual environment (VE) display, and vibrotactile and squeezing haptic feedback displays. A 1-DOF custom 3D printed gripper based on the da Vinci Surgical System master controls was used as the direct control interface. The aperture of the custom gripper was directly mapped to the position of the VE grippers, shown in Fig. 1a. Two surface electromyographic (EMG) electrodes were used as the myoelectric control interface and measured muscle activity from the flexor carpi radialis and extensor carpi radialis longus muscles using a Delsys Bagnoli EMG system. The magnitude of the muscle activity was mapped proportionally to the velocity of the VE grippers such that they closed when the wrist was flexed and opened when the wrist was extended. Data acquisition, control, and VE rendering were implemented through a Quanser Q8-USB DAQ with MATLAB/Simulink and QUARC real-time software.

N=4 (2 male, 2 female) individuals participated in the first pilot study and N=3 (2 male, 1 female) individuals participated in a second, follow-up study. All participants were consented according to a protocol approved by the Johns Hopkins University Homewood IRB (HIRB00005942). In Pilot Study II, one of the authors participated in the experiment.

B. Experimental Task

Participants were instructed to grasp and hold the virtual brittle object with the virtual gripper, as shown in Fig. 1a, while the object was pulled downward with a logarithmically increasing load force, $F_{\text{pull}}(t)$, as described below

$$F_{\text{pull}}(t) = K_{\text{f}} \ln(t+1) \tag{1}$$

where K_{f} is a gain that controls the difficulty of the force increase (integers ranged from 2-5) and t is the elapsed time in seconds since the start of the trial period. This load force function was empirically determined during VE development (prior to Pilot Studies I and II) to be more intuitive and provide appropriate task difficulty, and it is also consistent with observations in the literature [9], [10]. Participants did not directly feel the load force on the object; instead, they received feedback of the grip force they applied on the object through the haptic display. If participants produced too little grip force, the object slipped out of their grasp. On the other hand, producing grip force above a predetermined threshold caused the object to break (described in Section III-A and Section IV-A below).

Each trial began with a five-second preparation period, during which no force was applied to the object and no feedback was provided to the participant. Participants were allowed to move the virtual grippers until they were just touching the virtual object. At the end of the preparation period, the object disappeared and the pulling force on the object increased. No visual feedback of the object was provided. The trial ended after five seconds of a successful hold, or when the object broke or dropped. Both breaking and dropping the object were represented by the object reappearing as red. In addition, if the object slipped prior to breaking, the final position of the broken object was slightly lower relative to the grippers, in proportion to the amount of slip. Objects that were dropped reappeared falling to the bottom of the screen.

C. Haptic Feedback

A C-2 tactor (Engineering Acoustics, Inc.) was used to provide vibrotactile feedback. The squeezing display was based on work by Stanley and Kuchenbecker [11] and featured an MG90S servo that tightened a Velcro strap wrapped around the participant's wrist or bicep in proportion to the participant's grip force produced in the VE. The C-2 tactor and squeezing device were placed on the participant's ipsilateral forearm for the gripper interface, proximally to the control, as shown in Fig. 1c. To one-day accommodate transradial prostheses, the C-2 tactor and squeezing device were placed on the participant's ipsilateral bicep for the EMG interface, as shown in Fig. 1d.

The vibration feedback frequency was fixed at 250 Hz while the amplitude, $a_{\text{v}}(t)$, was logarithmic [12] with respect to the slip velocity, $V_{\text{slip}}(t)$, of the virtual object as

$$a_{\text{v}}(t) = \begin{cases} \phi(t) & 0 \le \phi(t) < 255 \\ 255 & \phi(t) \ge 255 \\ 0 & \text{otherwise} \end{cases}$$
$$\phi(t) = K_{\text{v}} \ln\left(2 \cdot \left|V_{\text{slip}}(t)\right| + 0.6\right) + 102 \tag{2}$$

where K_{v} is a gain applied to scale the amplitude for anticipated object slip velocities and 255 is the maximum vibrotactile output command. The amplitude was rate limited to provide smooth feedback.

D. Metrics

Task performance was assessed with the following metrics: percent broken, percent dropped, percent recovered from slip, and grip force difference integral. Percent broken (% broken) is the percentage of trials in which the object breaking force threshold was exceeded. Percent dropped (% dropped) is the percentage of trials in which the object slipped and dropped from the participant's grasp. Percent recovered from slip (% recovered) is the percentage of trials in which the object began to slip, but the participant prevented it from slipping further by increasing their grip force. Grip force difference integral, γ, is the integral of the positive difference between the participant's grip force, $F_{\text{g}}(t)$, and the theoretical minimum grip force required to hold the object, $F_{\min}(t)$, as calculated by

$$\gamma \equiv \begin{cases} \int_0^{t_{\text{f}}} \left(F_{\text{g}} - F_{\min}\right) dt & \left(F_{\text{g}} - F_{\min}\right) \ge 0 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where $t_{\text{f}} = 5$s. γ was evaluated only for successful trials.

TABLE I
TASK PERFORMANCE MEASURES (MEAN AND STANDARD DEVIATION) FROM N = 4 PARTICIPANTS USING DIRECT CONTROL

	% broken	% dropped	% recovered	γ [Ns]
None	9 ± 12	48 ± 38	18 ± 24	13 ± 8
Vibration	22 ± 6	28 ± 26	67 ± 35	8 ± 6
Squeeze	0	56 ± 30	27 ± 21	5 ± 3
Dual	23 ± 22	29 ± 36	61 ± 38	10 ± 6

III. PILOT STUDY 1 (DIRECT CONTROL)

All four participants completed the task with the gripper interface.

A. Methods

Participants completed four practice trials with visual feedback of the object to familiarize themselves with the control interface, feedback, and task. Afterward, each participant completed eight trials of the task in each of four conditions (32 trials total): no feedback (None), vibrotactile feedback only (Vibration), squeezing feedback only (Squeeze), and dual vibrotactile and squeezing feedback (Dual). The order of these conditions was counterbalanced to reduce learning effects. The four different pulling forces described by K_{f} in Eq. (1) were randomly presented twice for each condition. The breaking force was constant at 10 N. After completing all eight trials for a given condition, participants completed a questionnaire based on the NASA-TLX assessment.

B. Results

Task performance results for Pilot Study I are shown in Table I. There was notably 0% broken for Squeeze and 9% broken for None, on average. For % dropped, Vibration and Dual had similar results, with 28% dropped for Vibration and 29% dropped for Dual, on average. Likewise, for % recovered from slip, Vibration showed 67% recovered, while Dual showed 61% recovered, on average. Results for grip force difference integral were nearly all overlapping in margins of uncertainty.

In the questionnaires, multiple participants expressed that they needed more time to fully understand how to interpret the feedback cues in relation to their control of the virtual grippers and the task objective.

IV. PILOT STUDY II (MYOELECTRIC CONTROL)

All three participants completed the experiment with the EMG interface. Participant 1 had extensive experience with myoelectric control prior to the experiment, while participants 2 and 3 had little to no experience. Based on questionnaire responses and researcher observations from Pilot Study I, changes to the general protocol were made to improve the experimental design. These include increasing the training time, adding a second breaking threshold to prevent guessing, and including the no-feedback condition as a baseline comparison. Details of these changes are explained below.

A. Methods

EMG Practice Task: Participants using EMG control completed a position-tracking task in the VE prior to the experimental task. This task allowed participants to familiarize themselves with the myoelectric control and provided a quantitative measure of their quality of control, which could be used to account for experience. Participants completed two 30-second trials in which they controlled one sphere to track a target sphere moving in 1-D with a sinusoidal motion, as shown in Fig. 1b. The equations governing the target sphere motion for two levels of difficulty were

$$x_{\text{target}}(t) = \begin{cases} 2\sin(t) & \text{Trial 1} \\ \frac{4}{3}\sin\left(\frac{t}{3}\right) + \frac{4}{3}\sin\left(\frac{4t}{3}\right) & \text{Trial 2} \end{cases} \tag{4}$$

where t is the elapsed time since the start of the trial and x_{target} is the horizontal position of the target sphere from the center.

EMG Practice Task Metrics: Two metrics were defined to measure participants' accuracy and smoothness with EMG control. Position RMSE was defined as the root-mean-square error between the participant's sphere position and the target sphere position. Jerk RMSE was defined as the root-mean-square error between the third time derivatives of the participant's sphere position and target sphere position.

Protocol and Metrics: After being fitted with the electrodes, participants completed an EMG calibration based on the methods in Thomas *et al.* [13]. Participants then performed the EMG practice task before watching a video highlighting the main task phases and the possible task outcomes to aid their understanding of the task. After watching the video, participants performed an extended task training. Rather than complete only four total practice trials without any feedback, participants completed four practice trials for each feedback condition, in a fixed order. Visual feedback was provided only for the first trial of each condition. A constant virtual force of 4.9 N was added to the pulling force described in Eq. (1). Also, since we suspected that participants may have learned the single breaking force in the first study, low and high thresholds were introduced for each of the four pulling forces, given by

$$F_{\text{break}} = F_{\text{pull}}(t = 5s) + \begin{cases} 4 & \text{Low} \\ 6 & \text{High} \end{cases} \tag{5}$$

Each pulling force and breaking threshold was presented twice for each condition, such that each condition block consisted of 16 trials, for a total of 64 trials. All participants completed the no-feedback condition first as a control baseline, while the three other conditions were counterbalanced to mitigate learning effects.

In Pilot Study I, grip force difference integral was computed only for successful full-length trials, since the metric accumulated force difference over a fixed trial duration of 5 seconds. After Pilot Study I, for trials in which participants recovered from a slip event, it became of interest to compare participant's grasp before slip to their grasp after slip. Since intervals before slip and after slip are unlikely to be the same duration, a large force difference over a short duration and a small force difference over a long duration could inadvertently result in very similar values of grip force difference integral. For this reason, grip force difference integral was replaced with grasp economy, which accounts for differences in duration and enables comparison between the separate calculations of grasp economy for intervals before and after slip. Grasp economy (η) was defined as the RMSE between the participant's virtual grip force and the theoretical minimum grip force.

$$\eta \equiv \sqrt{\frac{1}{t_f}\int_0^{t_f}\left(F_g - F_{\min}\right)^2 dt} \tag{6}$$

where F_g, $F_{\min}$, and t_f are as defined in Eq. (3). Table II presents only the post-slip grasp economy (of a single slip) since all trials were found to exhibit slip at the beginning of the trial.

Statistical Analysis: Generalized linear mixed effects (GLME) models were used to analyze the main task metrics. Logistic mixed effects models were used for % broken, % dropped, and % recovered, while a linear mixed effects model was used for grasp economy (η). For all models, participants were random effects and feedback condition, trial number, pulling force, and breaking force were fixed effects.

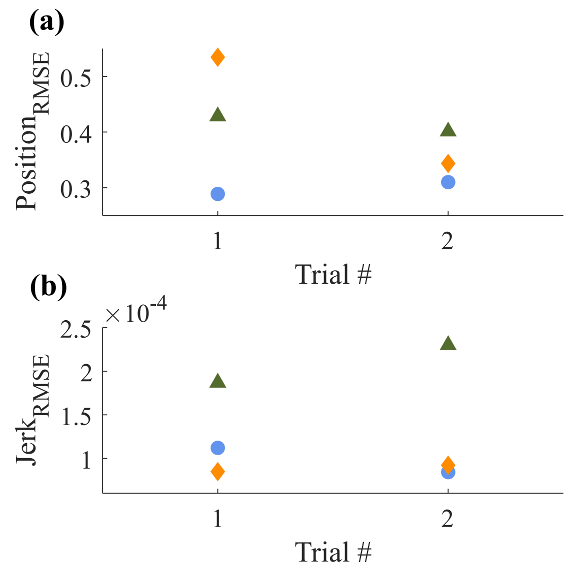

Fig. 2. Individual (a) position RSME and (b) jerk RMSE results for each participant performing both trials of the EMG practice task. Subjects 1, 2, and 3 are plotted as blue circles, orange diamonds, and green triangles, respectively.

TABLE II
TASK PERFORMANCE MEASURES (MEAN AND STANDARD DEVIATION) FROM N = 3 PARTICIPANTS USING MYOELECTRIC CONTROL

	% broken	% dropped	% recovered	η [N]
None	23 ± 14	65 ± 31	13 ± 22	5.7 ± 1.6
Vibration	46 ± 4	33 ± 22	21 ± 22	6.6 ± 1.9
Squeeze	33 ± 20	44 ± 19	23 ± 25	7.1 ± 1.5
Dual	33 ± 10	46 ± 22	21 ± 20	6.6 ± 1.6

B. Results

Results from the EMG task are shown in Fig. 2. Participant 1 had the lowest position RMSE for both trials, while Participant 3 had the largest jerk RMSE for both trials.

For the main task, there was a significant fixed effect of pulling force ($\beta = -0.278$, $SE = 0.084$, $p = 0.0016$) and trial number ($\beta = 0.027$, $SE = 0.014$, $p = 0.047$) for % broken. For % dropped, there was also a significant effect of pulling force ($\beta = 0.343$, $SE = 0.089$, $p < 0.001$). Participants were significantly less likely to drop the object ($\beta = -0.674$, $SE = 0.340$, $p = 0.048$) and more likely to recover the object ($\beta = 1.362$, $SE = 0.455$, $p = 0.0054$) for trials with a high breaking force than those with a low breaking force. Results also revealed that all trials involved slip at the start of the trial, so η was only computed for successful trials post-slip. There was significantly higher η for trials with high breaking force than those with low breaking force ($\beta = 1.406$, $SE = 0.42$, $p = 0.00195$). η was also significantly higher for Vibration ($\beta = 7.739$, $SE = 3.462$, $p = 0.0314$) than for None ($\beta = 5.717$, $SE = 2.639$). For Vibration, η decreased with an increase in pulling force, with respect to None ($\beta = -0.650$, $SE = 0.300$, $p = 0.0367$). No other effects were significant.

Table II displays the task performance results. Squeeze and Dual had similar results: 33% broken for both, 44% and 46% dropped, and 23% and 21% recovered, respectively. Vibration resulted in 46% broken and 33% dropped. None had 65% dropped and 13% recovered.

Fig. 3 shows the interaction between break and drop outcomes for each participant, separated by breaking force threshold and feedback. 0% success lies along the line between 100% broken and 100% dropped. The cluster of points in the bottom left corner of Fig. 3a suggests that Participant 1 had moderate task success (43.8% recovered). As seen in Fig. 3c, Participant 3's points lie along this line, signaling

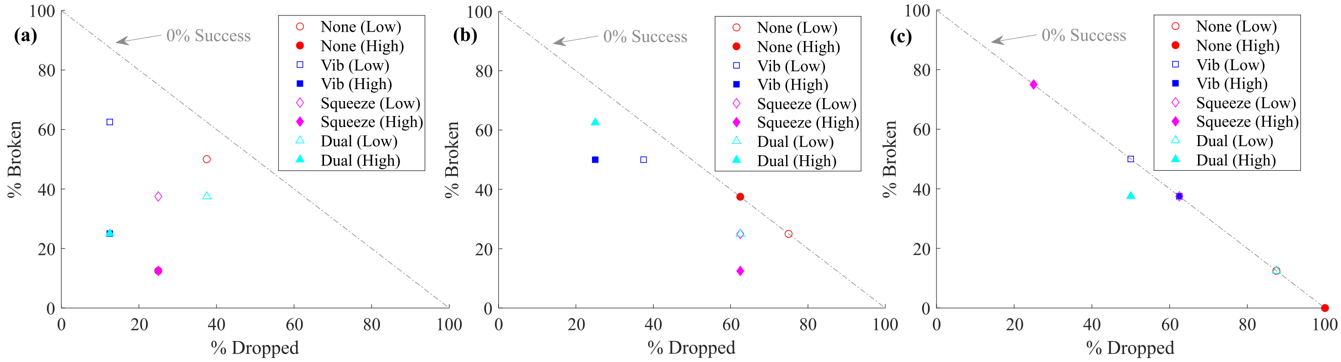

Fig. 3. % Broken versus % dropped, grouped by feedback and breaking force for Participants (a) 1 (b) 2 (c) 3.

very little task success (1.6% recovered). In Fig. 3b, Participant 2 appears to have had a level of success in between Participants 1 and 3 (12.5% recovered). Participants 1 and 2 had lower % dropped for all Vibration trials and high breaking force Dual trials. Another observation is the separation in outcomes by breaking force for Dual for Participants 1 and 2.

V. Discussion

Pilot Study I: Preliminary results suggest that squeeze cues were effective for preventing object break, but participants may have used proprioception to guess the single breaking force based on gripper aperture. Vibration and Dual results for % broken, % dropped, and % recovered were similar, indicating that vibration may have dominated the squeeze cue. Results for grip force difference integral are inconclusive but may indicate that receiving any feedback is better than receiving none. The large standard deviations suggest high variability between individuals. Taking the variability into account alongside the survey results, participants likely could have benefited from longer practice featuring the feedback sensations to better conceptualize the task.

Pilot Study II: The results from the GLME models above reveal the influence of the pulling force and breaking force threshold on task performance. These trends follow intuition, suggesting that our experimental framework is well-suited to test our overarching hypothesis regarding the utility of dual-modality haptic feedback; however, a larger sample size is needed for stronger conclusions.

The differing patterns in Fig. 3 suggest that each participant had varying strategies and levels of success. It is also possible that participants changed their focus and strategy throughout the experiment. In questionnaires, Participant 1 reported intuitive EMG control while Participant 3 reported unresponsive control. While the task was non-trivial for all participants, it is evident that Participant 3's difficulties with EMG control greatly impacted their ability to successfully perform the task. The differences in myoelectric control experience between Participants 1 and 3 viewed alongside their task performance differences suggest the importance of myoelectric control training to grasping performance. The EMG practice task results in Fig. 2 do show higher position and jerk error for Participant 3 compared to Participant 1, showing promise that the task can be used as a measure of a participant's control ability. However, Participant 3 did record that their control felt more responsive during the EMG practice task than during the main task, suggesting there exists room for improvement for the EMG practice task to better represent the main task.

VI. Future Work

The overall lack of clear trends regarding the comparison between Dual, Vibration, and Squeeze aligns with previous literature investigating multimodality and single-modality feedback. Future work will include a full-length study for both control interfaces using the updated protocol and study design. The modifications made for the myoelectric control study will hopefully address the potential confounds regarding poor task understanding and single breaking force in the gripper control study. To overcome the limitations of the EMG practice task in accounting for experience, a future EMG practice task may include a trial without visual feedback of the participant-controlled sphere to more closely reflect the feedforward nature of the main task. This task may be modified to measure direct control experience and skill. Additionally, quantitative methods for assessing mental effort with both single-modality and multimodality continuous haptic feedback, and comparisons between gripper and EMG control methods will be explored.

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