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# On the role of wearable haptics for force feedback in teleimpedance control for dual-arm robotic teleoperation

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*Abstract*— **Robotic teleoperation enables humans to safely complete exploratory procedures in remote locations for applications such as deep sea exploration or building assessments following natural disasters. Successful task completion requires meaningful dual arm robotic coordination and proper understanding of the environment. While these capabilities are inherent to humans via impedance regulation and haptic interactions, they can be challenging to achieve in telerobotic systems. Teleimpedance control has allowed impedance regulation in such applications, and bilateral teleoperation systems aim to restore haptic sensation to the operator, though often at the expense of stability or workspace size. *Wearable* haptic devices have the potential to apprise the operator of key forces during task completion while maintaining stability and transparency. In this paper, we evaluate the impact of wearable haptics for force feedback in teleimpedance control for dual-arm robotic teleoperation. Participants completed a peg-in-hole, box placement task, aiming to seat as many boxes as possible within the trial period. Experiments were conducted both transparent and opaque boxes. With the opaque box, participants achieved a higher number of successful placements with haptic feedback, and we saw higher mean interaction forces. Results suggest that the provision of wearable haptic feedback may increase confidence when visual cues are obscured.**

## I. INTRODUCTION

Teleoperation, by definition, is control of a robot located remotely from the operator. To improve operator speed and dexterity, force feedback is often introduced, though it comes with limitations. There are two primary objectives in a bilateral teleoperation scenario. First, the interactions must remain stable. Second, the system should be transparent, so that the operator does not experience the dynamics of the teleoperation system, but rather the remote task. In applications such as building inspections following natural disasters, robots offer the potential to provide the necessary assessments, while keeping their human operators at a safe distance. Requirements for these robots in building inspections emphasize operability and manipulation, [1], [2], aspects that heavily depend on feedback to the operator. In undersea applications, the presence of force feedback has been shown to reduce damage to work sites, and to the actual manipulator, though the use of grounded force feedback requires large amounts of training for successful use [3].

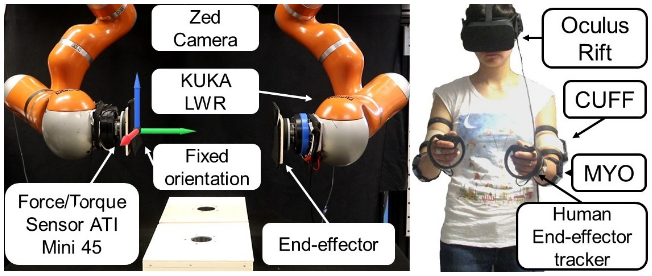

Fig. 1. The proposed teleimpedance with wearable haptic feedback scenario. (Right) Pilot interface with Oculus rift for visual feedback, EMG armband, force feedback CUFF, and human motion tracker. (Left) The framework is composed of a stereo camera and 2 KUKA LWR equipped with ATI Mini 45 force/torque sensor.

The role of force feedback and its impact on stability has been recognized since the 1960s [4]. The trade-offs between stability and transparency that are experienced in bilateral teleoperation systems have also been well-studied, and have led to a recommendation of providing force feedback to locations on the operator that are separate from where the command input is captured. The addition of kinesthetic force feedback co-located with control input adds latencies to the system, and can result in transmission delay and reflected force feedback [5], [6]. Various approaches have been proposed to address these challenges, including passivity-based approaches [7], model-based feedback via virtual environments [8], or sensory substitution. The sensory substitution method is a promising approach that relies on visual, auditory, or tactile feedback to apprise the user of forces present between the robot and its environment [9], [10], and is an area of active research.

Teleimpedance is an approach to teleoperation where user limb endpoint position and impedance are mapped to the teleoperated robot [11]. Proposed to overcome stability limitations of bilateral teleoperation, this unilateral approach does not include force feedback to the user, nor does it require a master haptic interface. The teleoperation paradigm maintains desired transparency, and features additional benefits observed in human behaviour. Joint stiffnesses are correlated to the stiffness of the user, introducing advantages such as safety, energy efficiency, and robustness [12].

While the teleimpedance framework offers numerous advantages in terms of stability and robustness compared to

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bilateral teleoperation, the approach still lacks useful haptic feedback to the operator. Wearable haptic devices, such as those proposed by Bianchi et al., offer a unique opportunity to improve the teleimpedance framework [13]. Wearable haptic feedback systems offer a range of actuation modes such as stretch, vibration, and squeeze, and these cues can be used to convey many types of stimuli, including proprioceptive information, navigation cues, and force feedback [14], [15], [16]. In the teleimpedance scenario, tactile cues that correlate to some key aspect of the robot's environment can be provided at a location distant from the control input, ensuring stability. In a previous study, this pairing between wearable haptics and teleimpedance was shown to benefit task completion in a single arm telerobotic system, where the haptic device provided feedback on the force of hand closure. When this feedback was provided, performance exceeded that of the open-loop system.

In this work, we explore the benefits of wearable haptic feedback in a dual-arm teleoperation scenario. Here, the CUFF (Clenching Upper-limb Force Feedback) is used to map two force components from the contact interaction at the end-effector, as compared to the single grip force of a robotic hand that was provided in prior work [17]. Two peg-in-hole type experiments are presented, one with visual feedback of the interaction via a transparent box, and the second with an opaque wooden box, obstructing view of the peg and hole. We hypothesize that the addition of interaction force feedback via the CUFF will result in a higher number of successful task completions, and improve force modulation. The dual-arm task design offers the opportunity to convey two aspects related to the interaction, the normal contact force and the shear force due to gravity, leveraging both the squeeze and the twist components of the CUFF. The system demonstrates the potential to leverage the efficiencies of teleimpedance and the intuitive nature of wearable haptic devices in an integrated environment.

## II. TELE-ROBOTIC PLATFORM

The tele-robotic platform consists of three main parts, the bimanual manipualtor (Fig. 1 left panel), the CUFF wearable haptic feedback system, and the pilot control station (Fig. 1, right panel). A teleimpedance framework is adopted to map the position and stiffness intentions of the pilot in the robot actions. A virtual reality headset, combined with the use of RGB stereo cameras, is used to provide immersive visual feedback to the pilot. A wearable force-feedback haptic device completes the working framework.

### A. Bimanual Manipulator

The bimanual platform consists of two anthropomorphic manipulators (KUKA LWR (Active Variable Impedance)) equipped with a neoprene covered wooden plate End-Effector (EE) (see Fig. 1). The wrench at the EE is measured by an ATI Mini 45 force-torque sensor placed between the last robot link and the EE. The KUKA LWR arms are mounted in a bimanual configuration. An RGB stereo camera (Stereolabs Zed Camera Mini[1]) is mounted between the two arms, and is used to retrieve video of the workspace that is streamed to the virtual reality headset.

*1) Teleimpedance:* Teleimpedance is a unilateral teleoperation framework in which position and impedance references are sent to the robot to improve the interaction between robot and environment. We adopt the common-mode teleimpedance setup (see [11]). The inverse kinematics of both robotic arms are computed with Priority Inverse Kinematics. The pose of robot's EE is the high priority task given by the pose of pilot's hand, whereas Cartesian position of fourth joint is secondary, to avoid obstruction during the task or camera occlusion. In our setup, the orientation of the EE is fixed (vertical to the floor, facing inward toward the opposite arm (see Fig. 1) to limit cognitive loading.

The Cartesian control law[2] for the KUKA LWR is:

$$\tau_{cmd} = J^T(k_c(X_{FRI} - X_{msr})) + D(d_c) + f_{dynamics}(q, \dot{q}, \ddot{q}) \quad (1)$$

where $k_c$ is the Cartesian stiffness, $J$ is the Jacobian, $D(d_c)$ is a dependent term of the damping value $d_c$, $f_{dynamics}$ is the dynamic model, and $X_{FRI}$ and $X_{msr}$ are the reference and measured Cartesian positions.

*2) Force Estimation:* The forces from the ATI are measured in the EE frame. Since the EE remains stationary relative to the task, the z components, normal to the plate surface, are attributed to the normal interaction forces and are used to calculate the squeeze component on the CUFF (Sec.1 and Fig. 1). The force vector is then transformed into the world frame using the known kinematics of the robotic arm, and the downward gravitational component is used to control the twist component on the CUFF.

In a calibration sequence, the CUFF is squeezed around the operators arm until a minimum current value is reached, 45 mA, and repeated for a large maximum current value, 120 mA, is reached. These values are recorded and used to scale the normal force measurements, between 0-100N, to ensure the band on the CUFF does not develop slack during use, and does not squeeze their arm too hard. The tangential forces can be in either direction, and the motors can turn up to 450° in either direction, corresponding to a maximum expected tangential force of 5 N from pilot data.

### B. Pilot Interface

Operator movements are obtained with an Oculus Rift[3] (Fig. 1). The user's hand position, given by Oculus joystick, is mapped to the robot EE pose. The reference pose is rescaled as a function of robot and user arm lengths. Regarding the visual feedback, the left and right images retrieved from the Zed Camera Mini are streamed to the Virtual Reality Headset with a resolution of 720p and 60 fps.

The framework employed for managing impedance includes a wearable device equipped with eight surface electromyographic (EMG) electrodes (MYO Armband[4]). The

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[1] https://www.stereolabs.com/

[2] KUKA FRI 10, Manual for KUKA System Software 5.6 lr

[3] https://www.oculus.com/

[4] https://www.myo.com/

Cartesian stiffness $k_c$ is derived from EMG on the forearm, calculated as proportional to the average of the readings from the band. This value is the desired stiffness at the EE in Cartesian space, and the necessary joint stiffnesses are then calculated using the current manipulator kinematics.

### C. Wearable Haptic Feedback System

The wearable CUFF device produces distributed mechano-tactile stimulation using both normal and tangential forces [16]. The CUFF consists of two DC motors attached to a band worn around the users arm. When the motors spin in the same direction, the fabric conveys tangential force cues. When the motors spin in opposite directions, they squeeze the belt around the arm, conveying a normal force.

## III. METHODS

### A. Task Description

To evaluate the benefit of providing wearable haptic feedback in a dual-arm teleimpedance peg-in-hole type task, subjects were asked to manipulate and position a 20 cm cube box such that a peg mounted on the bottom of the box was inserted into a hole in the task environment (1 mm tolerance in diameter). The participant was required teleoperate the dual-arm system to grab the box from the experimenter's hands and seat the box into the base (see Fig. 1). The task was completed first with a transparent cube, with clear sides, and then with a wood-faced cube, which obstructed the participants' view of the peg and base (see Fig. 2).

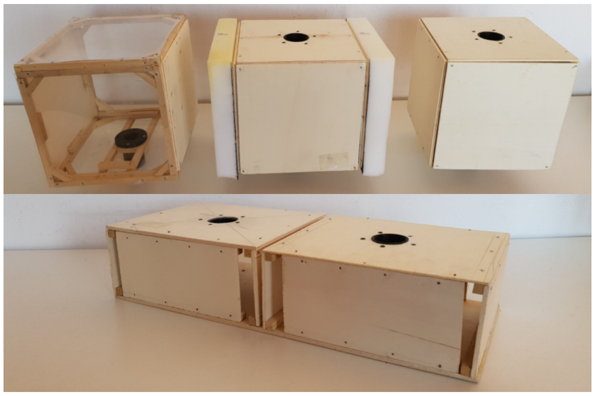


Fig. 2. The participants must grasp one of the task boxes (top), either transparent box (left), training box (center) and opaque box (right), and seat it in the base (bottom) in front of the robotic manipulators.

### B. Training

For both the transparent and opaque boxes, a ten minute training session was administered before commencing the experiment to familiarize the participant with the hardware, feedback components, and task objectives. The participant was asked to move their arms and explore the reachable workspace of the robot. The box base was moved to ensure box placements were in a natural and comfortable position for the participant. Next, the experimenter pressed on the end-effector to create normal and tangential forces, explaining the mapping of the CUFF wearable haptic feedback in the process. The participant was asked to grasp the box with medium density foam attached to the sides (see Fig. 2), and with the experimenter still holding the box, modulate the force on the box and note the resulting normal force cues from the CUFF. Next, subjects grasped another box, without foam, while the experimenter pushed on the box from above, demonstrating the tangential feedback cue of the CUFF. Lastly, the experimenter held the box out directly in front of the robotic arms, and the subject grasped the box and seated it in the base. Training concluded when the participant felt comfortable with the task.

### C. Experimental Protocol

Subjects were asked to take a box from the experimenter and place it in the base as many times as possible in a five minute trial. Each time the participant released the box, the experimenter held it up again. In the case of an emergency stop event (due to reaching a torque or force limit), time recording was paused and resumed after resetting the system. The experimenter tapped the end-effectors simultaneously at the start of each trial or restart to synchronize the video to the recorded data. Participants completed the task twice, one time with CUFF feedback, and one time without. Half of the subjects complete the trials with haptic feedback first, and the other half completed the trials with no feedback first.

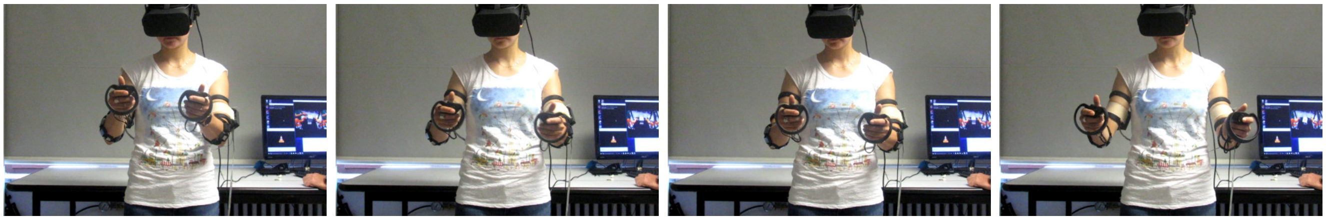
### D. Participants

Eleven participants, (age $28 \pm 2$ years, 7 female), all novices to teleoperation control, completed the task with the transparent block. Eleven participants, (age $29 \pm 3$ years, 4 female, 1 left handed), all with approximately one half-hour of experience manipulating the transparent box (either in pilot experiments or because they participated in the transparent box experiment), completed the task with the opaque box. No participants claimed any physical or cognitive impairment that could interfere with their ability to follow the instructions of the study, nor any pathology that could affect tactile sensation or muscular activity of the upper arm. The methods and procedures described herein were carried out in accordance with the recommendations of the Institutional Review Board of University of Pisa with written informed consent obtained from all users.

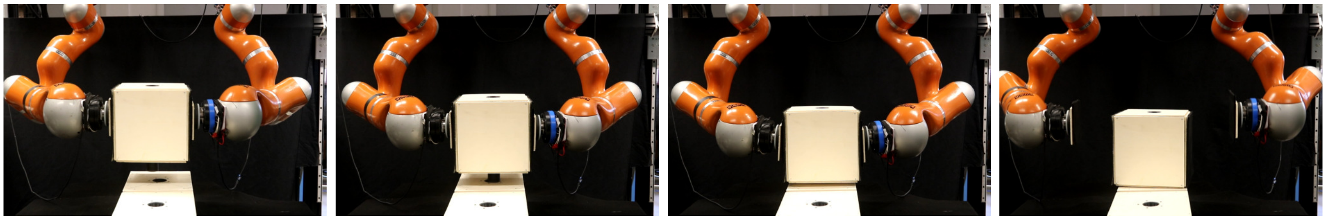
## IV. DATA ANALYSIS

Video recordings were used to synchronize data across the various components of the telerobotic platform, and to define the number of task completion attempts, the basis for computing our outcome metrics. Due to complexities in the experimental protocol and unsuitable video recordings for some cases, only the first three and a half minutes of the trials were included in the analysis, and 5 of the subjects in the transparent box task were excluded altogether, resulting in 6 participants (age $28 \pm 2$ years, 4 female) in the subsequent analysis. For the opaque box task, all subjects were included in the analysis with a full five minute trial time.

The video from the stereo camera was recorded along with the force readings from the ATI sensors. After the experiments were completed, the video was analyzed to identify



(a) Pilot



(b) Bimanual Platform

Fig. 3. Sequences show experimental process: user must grasp box and seat it into base, repeatedly with and without force feedback.

both the time stamps for the beginning and end of each attempt, as shown in Fig. 4, and if the subjects successfully completed the task. A successful attempt consisted of the box being seated in the base after release. The time stamps were then superimposed on the force data, and only force metrics from the successful attempts were considered. In each of the two experiments, four metrics were extracted from the attempts, namely the number of attempts to place the box in the base, the number of successful attempts, the mean force during each attempt, and the peak force for each attempt. The values for all attempts were averaged within each trial for each subject.

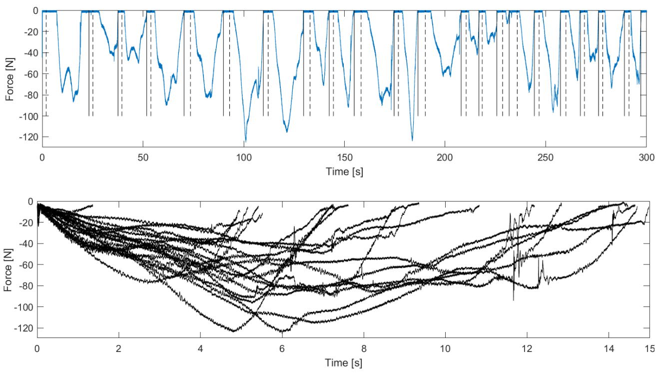


Fig. 4. Example force data for an experimental trial, segmented by the beginning (dashed) and end(solid) of each attempt. Below shows the overlaid force data for the segmented attempts.

## V. RESULTS

Four metrics were evaluated to determine the impact of wearable haptic feedback during dual-arm teleimpedance. Each of the four metrics was statistically analyzed to identify differences in each of the three design variables, and any subsequent interactions. Three variables were considered. *Feedback* compares trials with the presence of feedback (*On*) or without ($Off$), *Order* considers the order of the On and Off trials, where the On trials are tested first ($FB1$) or second ($FB2$), and *Trial* refers to the two trials ($T1$ and $T2$) completed with each Feedback condition. A 2 × 2 × 2 [Order ($FB1$; $FB2$) × Feedback (*On*; $Off$) × Trial ($T1$; $T2$)] ANOVA, with repeated-measures on the last two factors, was conducted. Sphericity violations were treated with a Huynh-Feldt adjustment as needed, and simple effects were analyzed using the False Discovery Rate (FDR) procedure.

*1) Transparent Box Task:* In the transparent box experiment, the number of attempts per trial for the *On* and $Off$ cases of *Feedback* had a mean and standard error of $12.50 \pm 1.80$ and $11.0 \pm 1.71$, for *Trial*, $11.17 \pm 1.46$ for $T1$ and $12.33 \pm 2.03$ for $T2$, and for *Order*, $14.25 \pm 2.45$ for $FB1$ and $9.25 \pm 2.44$ for $FB2$. *Feedback* did trend toward significance for the number of attempts, $F(1,4) = 6.75$, $p = .06$, $\eta_p^2 = 0.63$, though there were no other significant effects.

For the number of successful placement attempts the mean and standard error for the number of successes per trial for each of the conditions was as follows: for the *Feedback* condition, $8.17 \pm 1.91$ for *On* and $6.67 \pm 1.81$ for $Off$, for *Trial*, $6.67 \pm 1.44$ for $T1$ and $8.17 \pm 2.24$ for $T2$, and for *Order*, $9.92 \pm 2.59$ for $FB1$ and $4.92 \pm 2.59$ for $FB2$. There was a trend toward significance in the number of successes for *Feedback* ($F(1,4) = 6.48$, $p = .06$, $\eta_p^2 = 0.62$), though no other variables had significant main effects.

The peak force per successful placement attempt for the *Feedback* condition was $139.51 \pm 10.84$ N for *On* and $114.53 \pm 5.34$ N for $Off$, for *Trial*, $125.17 \pm 8.26$ N for $T1$ and $128.87 \pm 8.00$ N for $T2$, and for *Order*, $108.50 \pm 9.78$ N for $FB1$ and $145.54 \pm 9.78$ N for $FB2$. In investigating the main effects, there was a trend toward significance for both *Feedback* ($F(1,4) = 6.18$, $p = .07$, $\eta_p^2 = 0.61$) and *Order* ($F(1,4) = 7.17$, $p = .055$, $\eta_p^2 = 0.64$) for the peak force during attempts; no other variables had significant effects.

The mean force for all attempts had a mean and standard error for the *Feedback* condition of $57.18 \pm 7.88$ N for *On* and 44.07 ± 6.02 N for $Off$, for the *Trial*, 46.57 ± 5.38 N for $T1$ and 54.68 ± 7.10 N for $T2$, and for *Order*, 48.43 ± 8.02 N for $FB1$ and 52.82 ± 8.02 N for $FB2$. There were no significant main effects or interactions for the mean force across attempts in the transparent box experiment.

*2) Opaque Box Task:* The number of attempts per trial in the opaque box experiment had a mean and standard error for the *Feedback* condition of 22.63 ± 2.57 for *On* and 20.45 ± 2.77 for $Off$, for *Trial*, 20.62 ± 2.52 for $T1$ and 22.46 ± 2.77 for $T2$, and for *Order*, 22.13 ± 3.52 for $FB1$ and 20.95 ± 3.85 for $FB2$. The opaque box experiment did not have any significant effects for the number of attempts, though there was a trend toward a significant effect between the trials, $F(1,9) = 4.42$, $p = .065$, $\eta_p^2 = 0.33$. Regardless of the main effects, there were two significant interactions, between the *Trial* and *Feedback* presence, $F(1,9) = 6.72$, $p = .03$, $\eta_p^2 = 0.43$, and between the *Order* and *Feedback*, $F(1,9) = 6.66$, $p = .03$, $\eta_p^2 = 0.425$. When broken down by *Order*, there was a significant increase in attempts with feedback present if the feedback was given second, $F(1,4) = 21.06$, $p = .01$, $\eta_p^2 = 0.84$, though not if the feedback was given first. When broken down by *Feedback*, when the CUFF was inactive the second trial, $T2$, had more successes than $T1$, $F(1,9) = 9.373$, $p = .01$, $\eta_p^2 = 0.51$, but not when it was active.

The mean and standard error for the number of successes per trial for *Feedback* condition was 16.49 ± 2.04 for *On* and 13.61 ± 1.71 for $Off$, for *Trial*, 14.44 ± 1.85 for $T1$ and 15.66 ± 1.97 for $T2$, and for *Order*, 14.00 ± 2.41 for $FB1$ and 16.10 ± 2.64 for $FB2$. The sole significant main effect was for *Feedback* ($F(1,9) = 5.89$, $p = .04$, $\eta_p^2 = 0.40$), showing a higher number of successes with the feedback active, as well as a significant interaction between *Feedback* and *Order* ($F(1,9) = 5.23$, $p = .048$, $\eta_p^2 = 0.37$). When broken down by *Order*, there was a trend toward a significant increase in successes with the presence of feedback if the feedback is given second ($F(1,4) = 6.48$, $p = .059$, $\eta_p^2 = 0.631$), though none of the feedback was given first.

The mean and standard error of the peak force per trial for successful attempts for the *Feedback* condition was 110.00 ± 6.64 N for *On* and 99.24 ± 9.86 N for $Off$, for *Trial*, 103.92 ± 7.10 N for $T1$ and 105.32 ± 8.26 N for $T2$, and for *Order*, 97.82 ± 10.16 N for $FB1$ and 111.42 ± 11.13 N for $FB2$. There were no significant main effects or interactions for the peak forces in successful placement attempts.

The mean force for all placement attempts per trial had a mean and standard error for the *Feedback* condition of 65.56 ± 5.53 N for *On* and 55.43 ± 7.05 N for $Off$, for *Trial*, 60.55 ± 5.60 N for $T1$ and 60.44 ± 6.64 N for $T2$, and for *Order*, 55.74 ± 8.14 N for $FB1$ and 65.25 ± 8.92 N for $FB2$. The opaque box experiment had a significant effect of *Feedback*, with higher mean forces if the feedback was active, ($F(1,9) = 6.98$, $p = .03$, $\eta_p^2 = 0.44$), and no other variables had significant main effects or interactions.

## VI. DISCUSSION

We sought to explore the impact of providing wearable haptic feedback to a human operator when completing a dual-arm teleoperation task in a teleimpedance scenario. Subjects were asked to grasp a customized box, with a peg on the bottom, from the the experimenter's hand, and place it on a base, as many times as possible within the trial time period. Participants completed the task two times in each of two conditions, with and without the CUFF feedback active. The experiment was conducted with both transparent boxes (novice users) and opaque boxes (experienced users).

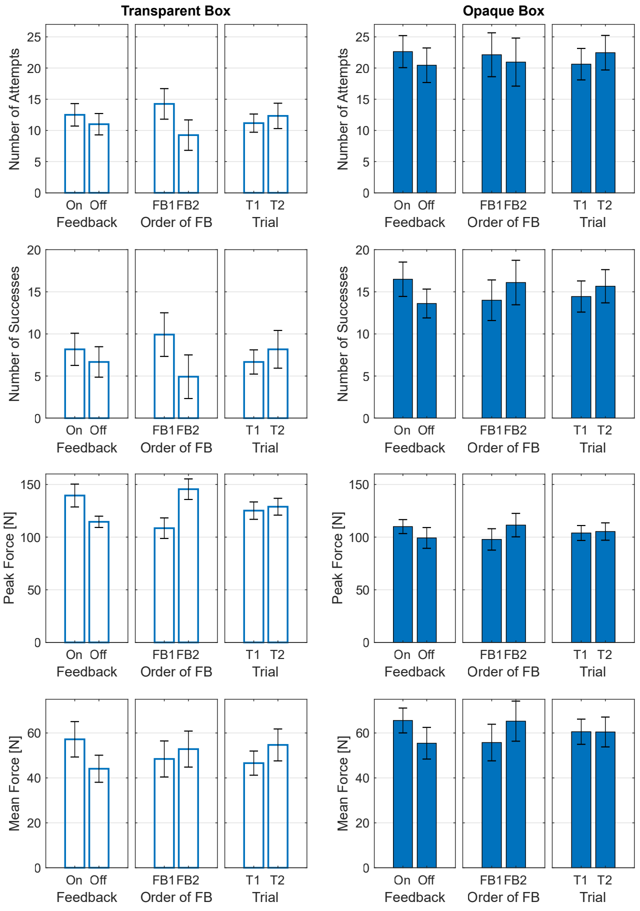


Fig. 5. The mean and standard error of the main effects for the number of attempts, successes, and the mean and peak forces for the successful attempts are represented for the transparent and opaque box experiments. *Feedback* compares performance between when the CUFF is (On) or (Off). *Order* compares performance of subjects who completed the feedback trials first (FB1) to those that used the CUFF second (FB2). *Trial* compares the performance between the first (T1) and second (T2) trial.

*1) Transparent Box Task:* In the transparent box task, participants were able to locate the hole in the base visually through the transparent box, and did so with and without the assistance of the CUFF. This reliance on visual feedback could have been the cause of no statistical differences in the metrics; vision frequently dominates the integrated visual haptic perception [18], particularly when the sensory noise is increased[19]. Though not statistically significant, there were two effects of the peak interaction forces that trend that toward significance. There were higher peak forces when the feedback was activated in the second trial. This was as expected if the CUFF was providing clarifying information about the task, which if given in the first trial carried over to the second trial when the feedback was turned off. In the opposite case, where the CUFF was introduced in the second trial, the participants may have struggled with the task in the first trial. However, the other main effect that approached significance was the overall impact of the feedback, which showed higher peak forces with the presence of feedback. There are a few possibilities for this result. The feedback could have been difficult to interpret and implement, or it could have been utilized in an unanticipated manner. Overall, the lack of statistical significance was likely due to reliance on visual feedback during the task, overriding any influence of the haptic feedback device.

*2) Opaque Box Task:* In the opaque box task, both the peg and the hole were obstructed from the participant's sight, though sight of the arms and box was maintained. It is not surprising that the number of successful box placements was higher when feedback is available. The total number of attempts with and without feedback was not significantly different; however, there were two significant interactions. First, both the number of attempts and number of successes demonstrated a significant interaction between feedback condition and order of presentation. Interestingly, the presence of feedback had no effect if it was presented in the first trial. In contrast, there were significantly more attempts made when feedback via the CUFF was introduced after participants completed the trial without feedback. The number of successes, while not significant, also followed this same trend. Since this interaction did not exist for the transparent box, it may be that the CUFF provided useful information to the user while they explored and understood the environment, and the repetitiveness of the placement task allowed for learning. If the participant experienced CUFF feedback before the no feedback case, they seemed to locate the position of the hole, possibly in terms of their body's kinematics, and then continue with relative proficiency after the CUFF feedback was removed. Alternatively, in the absence of CUFF feedback, the hole in the base was harder to locate, and so when feedback was provided later, users benefited and demonstrated improved performance. Second, there was a significant interaction between the feedback condition and number of attempts between the first and second trials. Further analysis showed the difference was only present in the trials without feedback, and we saw no difference between the attempts for trials with the CUFF activated, whether in the first and second trial. This result could further corroborate the previously stated hypothesis, where feedback allows the user to quickly accustom themselves to the task. In contrast, when feedback was inactive, there was a learning effect as they tried to complete the task without sensory feedback. This trend was not observed in the number of successes. This could suggest that rather than knowledge of the environment and task space, the results may indicate that users are gaining confidence in their task performance. Future work to investigate these phenomena is warranted.

The introduction of force feedback with the CUFF was expected to impact interaction forces between the robot's end-effector and the box. There was a significant difference in the mean normal forces between the feedback conditions during successful attempts. Unexpectedly, the forces were higher with active feedback. It is possible the CUFF served as a distraction or was difficult to interpret, however the effects on the number of attempts discussed above suggests it is more likely the participants were implementing the information in an unanticipated manner. Subjects may have been using the CUFF as a safety indicator rather than a representation of the robot's applied forces. During both training and the experiment, participants were instructed to maximize the number of seated boxes in the base, with no instruction on force regulation apart from staying below a threshold, which was conveyed during the feedback condition through a rapid oscillation of the CUFF. Once the box was grasped, increased contact forces were caused by the participant moving their hands closer together. Since the task objectives centered on speed and accuracy, not minimization of contact forces, a squeeze present in the CUFF informed the user of an adequate grip, and so long as the threshold warning wasn't activated, no other modulation was necessary to accomplish the task. In contrast, when the CUFF was inactive, participants had to be alert of hand distance since no warning was available. Unlike the transparent box task, for the opaque box the lack of visual feedback could have caused participants to be more cautious without the CUFF, and more dependent on the feedback when present as a contact and threshold indicator, resulting in larger forces overall. These are complex interactions that require further analysis of the participant's understanding of the system and impression of the feedback.

These findings present several future research avenues. Regarding the confidence of the participants to understand the environment, qualitative surveys should be conducted. The learning impact could be addressed by using multiple bases and randomly assigning targets or by stacking boxes to eliminate dependence on repetition. The use of the feedback and the intuitiveness of the force information should be tested by comparing a task focusing on force modulation rather than speed, as they may have conflicting objectives.

## VII. CONCLUSION

The impact of providing wearable haptic feedback for contact interactions in a peg-in-hole type dual arm teleoperation scenario was explored. The provision of wearable haptic feedback, here via the CUFF, may allow the participant to familiarize themselves with the task and environment more quickly, where without it there were observable learning effects. The addition of wearable haptic feedback resulted in higher contact forces and more successful box placements within the time constraint in the absence of visual feedback.

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