

Towards Telementoring for Needle Insertion: Effects of Haptic and Visual Feedback on Mentor Perception of Trainee Forces

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Abstract—Emergency needle decompression is a life-saving procedure performed to treat patients with air trapped between the chest wall and the lungs. This condition can severely compromise heart and lung function, almost always leading to death if untreated. However, the needle decompression task itself carries many potential risks and complications due to proximity to vital organs, particularly if the operator is not sufficiently trained. In this paper, we present a device to help facilitate needle decompression training in which a mentor can feel the needle insertion forces exerted by the trainee. We developed a custom 3D printed attachment for decompression needle with an embedded force sensor to relay axial force data from the needle to a Geomagic Touch haptic device. In our envisioned telementoring system, a remote expert will also be able to provide haptic cues related to needle guidance to the trainee. The main goal for this work is to evaluate the most effective form of visual, haptic, or combined feedback provided to the mentor on applied forces by the trainee. In our experiment, 15 subjects were recruited to act as mentors and reported their perception of needle insertion forces that were controlled by the experimenter (acting as a trainee) at three levels of force, and five feedback conditions. Results of the experiment yielded best performance in terms of accuracy for a combination of both graphic and haptic cues, with a median accuracy of 100% at correctly predicting the trainee applied force level.

I. INTRODUCTION

Severe chest injuries can cause tension pneumothorax, a life threatening condition where air is trapped in the pleural space, inside the thorax but outside of the lungs. In addition to trauma, this condition can be caused by biopsies [1], and has been observed as a rare complication of Covid-19 [2], [3]. The abnormal pressure causes displacement of structures between the lungs, including the heart, potentially causing cardiac arrest. At the same time, the lungs may also collapse in the area where air is present. Needle decompression is a procedure where a needle is inserted in the affected area to remove excess air. When done successfully, this is life-saving procedure. However, done incorrectly, the needle decompression task can cause injury to the heart and or lungs, with potential life-threatening consequences [4]–[6].

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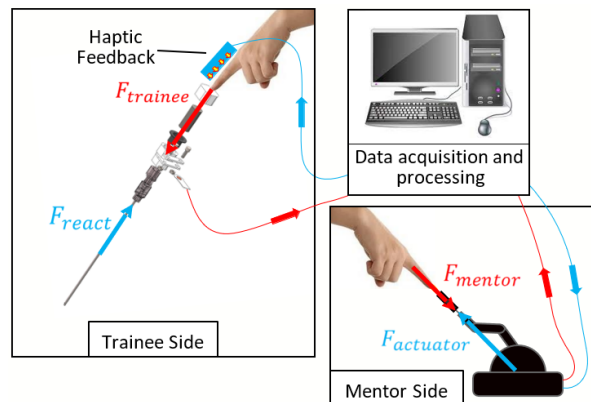


Fig. 1: Diagram of the envisioned full haptic telementoring system, including the trainee and mentor side. Trainees exert force on the needle which is read by a force sensor and sent to the ground haptic device for the mentor to feel as a linearly proportional force. The mentor can interact with the device to provide feedback back to the trainee.

Needle decompression failure rates have been reported as high as 76% [7], [8], which can be impacted by the thickness of the chest wall, location of the needle decompression, and technical human errors, highlighting a clear need for improvement in the application and execution of this technique [7], [9]. Outcomes can also be improved in the prehospital setting, where performed needle decompressions often turn out to be ineffective or unnecessary [10]–[12]. Simulation has been studied in this setting with improved performance in higher fidelity models [13]. Therefore, there is a clear benefit to providing better training to help first responders to successfully treat this condition.

Current training protocols for percutaneous needle insertion involve automated patient simulations and robotic systems [14]–[18]. However, none of these allow the mentor to monitor the forces exerted by a trainee. It was found that when visual feedback is limited, such as in an emergency when proper visual equipment is unattainable or difficult to set up, force feedback may be necessary to preform the task [19]. Therefore, in training conditions, where a novice has limited knowledge of the forces he/she should be exerting, it would be better to have an experienced mentor who could feel the same forces as the trainee and instruct the trainee accordingly. However, in coaching advanced skills, such as needle insertion, it is well known that a coach must emphasize implicit learning techniques so as not to distract or disrupt the trainee [20]–[22].

With this in mind, Basu et al. have used tactile guidance cues to guide learners about orientation and positioning of needle-like tools for training percutaneous needle insertion [23]. While it was found that tool space guidance was the easiest for trainees to follow and led to the least amount of error, this work did not consider the issue of delivering information to the expert mentor, nor did it provide a way to measure the force applied by the trainee. In this paper, we build upon the work of Basu et al. and extend training to allow a mentor to feel the forces being applied by the trainee in real-time. The end-goal is for the mentor to initiate feedback to the trainee, in the form of haptic cues that will direct them to insert the needle further or pull it back. This can be seen as the composition of two problems: (i) delivering accurate and compelling force feedback to the mentor that matches the physical force applied by the trainee, and (ii) delivering haptic feedback to the trainee to convey directions from the mentor. In this work, we present the design of a system to address both aspects, and conduct a user study to accomplish (i) by determining the best way to convey force feedback to the expert mentor, while evaluation of (ii) will be part of future work.

II. BACKGROUND

In addition to the factors specific to needle insertion tasks, there have been more general motivations for an increased interest in telemedicine and telerobotics in recent years. These include the possibility of delivering high level of expertise to underserved and rural communities, as well as the availability of technology that can make telerobotics a possibility [24]. Telerobotics has also been found to be comparable to in person training in terms of effectiveness, and has the potential to be very cost effective [25].

Traditionally, telerobotics was delivered through video-conferencing [26]. However, with the advance of technology, more sophisticated means of interaction, such as robotic systems, are being included [27]. Since the sense of touch is of paramount importance in medical procedures [28], it makes sense for haptic technology to play a role in telerobotics. In order to have a true sense of telepresence and interactive experience, this communication needs to be bidirectional (i.e., the trainee should be able to feel the expert guidance, while the expert should be able to feel the trainee's actions). In this paper, we focus on delivering cues to the expert to better perceive what the trainee is actually doing. For a needle insertion task, this means conveying information on how much force is being exchanged between the needle and the patient or simulated tissue.

Force feedback for needle insertion is usually delivered to provide information on forces applied by a surgical robot, and typically through a grounded haptic device [29], [30]. However, this is not the only possible way to convey force information, as visual feedback can also do this effectively [31], [32]. In fact, visual feedback was shown to be as or even more helpful than haptic feedback in a virtual reality needle insertion task [33]. Our goal in this paper is to consider visual as well as haptic feedback and to determine the best way to deliver force information to the mentor related to

the force applied by a trainee during a real world, physical needle insertion task.

III. SYSTEM DESIGN

In order to be able to deploy a system similar to the concept shown in Figure 1, two elements need to be present: (i) on the trainee side, a way to measure interaction forces and to convey feedback from the mentor, and (ii) on the mentor side, a way to deliver feedback on how much force is being applied by the trainee, as well as a way for the mentor to send a push/pull cue to guide needle insertion.

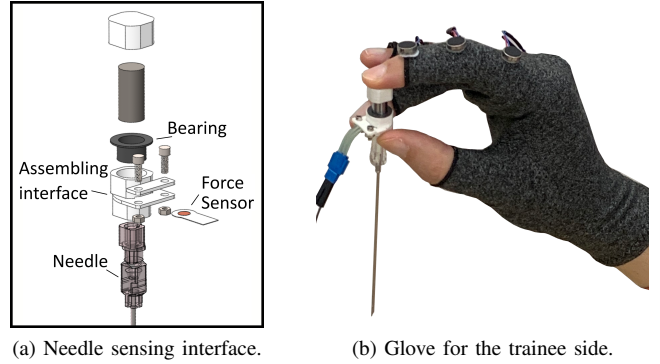


Fig. 2: Insertion force sensing attachment on the trainee side (a) with a prototype guidance feedback glove (b).

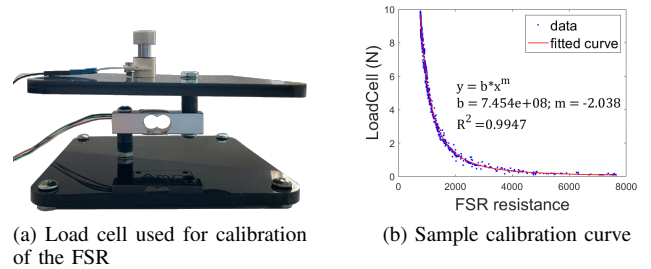


Fig. 3: The FSR sensor was calibrated using a load cell and using a power function fit.

A. Trainee Side

Figure 2a shows an overview of the sensing setup on the trainee side. A custom 3D-printed ABS attachment was designed to fit over a standard decompression needle. The attachment has two major parts, connected with a lightweight Igus polymer bearing. The top of the attachment consists of a bar with a cap for the trainee to push on. The second part consists of a force sensing resistor (FSR 400 from Interlink Electronics) can slide through a slot in the printed attachment, secured with a custom clamping mechanism. When the trainee uses the needle, this sensing interface is able to measure forces applied on the top of the attachment, which presses against the FSR sensor.

The FSR sensor itself was calibrated for force measurement up to 10N using a load cell as shown in Figure 3a: the sensing base is placed on top of the load cell, and then a force is gradually applied on the cap until the load cell reads

above 10N. This is repeated ten times. Figure 3b shows a sample calibration. We found that a power fitting yielded a good mapping of resistance values from the FSR to force. This calibration procedure takes approximately five minutes, making it easy to calibrate the sensor as needed.

Finally, Figure 2b shows a prototype for the wearable haptic feedback interface for the trainee. This is done with a glove and three vibrotactile motors (ROB-08449, Sparkfun), which are activated in sequence to signal an insertion or extraction command, with a distal-to-proximal activation signifying insertion and a proximal-to-distal activation signifying extraction. This is similar to what was done in [23] to deliver directional cues.

B. Mentor Side

Information on the force applied to the needle is delivered to the mentor through a Geomagic Touch haptic device and a virtual reality environment built with CHAI3D [34]. In this paper, we consider different combinations of haptic feedback from the device and visual feedback in the virtual environment to convey information to the mentor. Visual feedback is obtained in through a virtual semi transparent "ghost" end-effector that extrudes from the base needle representation based on the force detected on the needle. We refer to section IV-A for more details and pictures.

The haptic feedback delivered to the trainee is based on vertical movement of the stylus by the mentor. Haptic feedback to the trainee is not always active to prevent accidental signals from being sent, but is activated by a button press on the haptic device. Since this is a two-person system, validation needs to be done on the effectiveness of both the haptic feedback to the trainee and feedback to the mentor. In the following sections we will describe our experimental setup and results for validation of feedback to the mentor, leaving evaluation of feedback to the trainee for future work.

IV. METHODS

A. Rendering Feedback

In this section, we present an experimental setup to test different forms of feedback for the mentor, and evaluate them based on force classification accuracy. We considered

Condition label	Feedback provided
C1	Graphics and pushing
C2	Graphics and pulling
C3	Graphics
C4	Pushing
C5	Pulling

TABLE I: Different conditions for user's feedback

three forms of feedback: (i) haptic feedback in the form of pushing against the trainee's direction of movement, (ii) haptic feedback by pulling along the trainee's direction of movement, and (iii) visual feedback (Fig. 4). These types of feedback were provided individually, but also as combinations of visual and haptic feedback, leading to five different conditions as shown in Table I.

The magnitude of haptic feedback is proportional to the force sensor signal on the instrumented spinal needle, and it is mapped to the Z axis of the haptic device. For pushing conditions (i.e., C1 and C4), positive haptic feedback is employed, i.e., as the trainee pushes the needle down, the Touch device renders a reaction force that pushes the mentor's hand up (Fig. 4a), as if the mentor themselves was inserting the needle. For pulling conditions (i.e., C2 and C5), negative haptic feedback is employed where the haptic device will pull on the mentor as the trainee pushes down on the needle (Fig. 4b). This aims to simulate real world training conditions for needle insertion, where the mentor would hold the trainee's hand back as they perform an insertion.

For the graphical display, a ghost needle provides visual feedback. This ghost needle is a projection of the needle's force along the axis of the stylus (Fig. 4c). The graphical displacement is proportional to both the amount of force measured on the needle and the displacement of the stylus from the zero position, meaning the mentor can magnify the visual feedback by moving the stylus. This was chosen over a fixed displacement based on the amount of force in a pilot study, where the fixed displacement was reported to feel distractive and unresponsive, while multiplying by the position-dependent gain increased the sense of control over

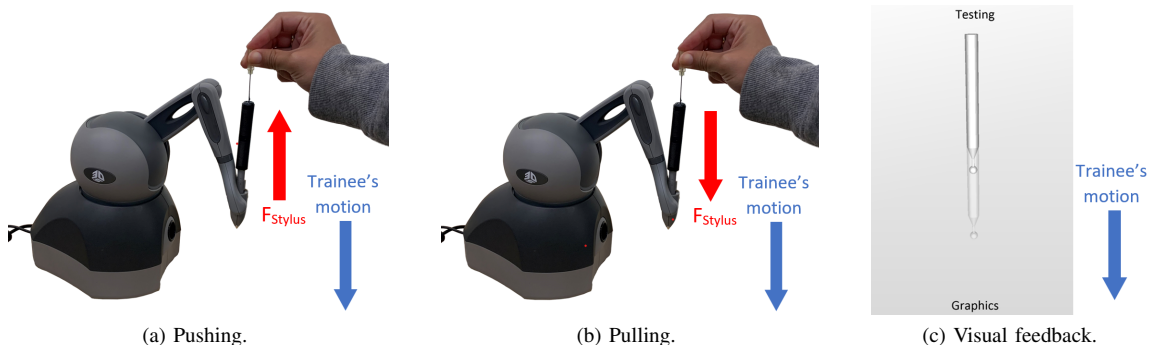


Fig. 4: Forms of feedback. (a) pushing, where the stylus of the haptic device moves opposite to the direction of the trainee's motion (b) pulling, where the stylus moves in the direction of the trainee's motion (c) graphics, where a transparent "ghost" needle is a projection of the trainee's needle and an opaque needle visualizes the haptic stylus.

the simulation.

B. Experimental Protocol

The experiment included 15 naive participants (mean age: 23 ± 3.21 , four female). Participants did not suffer from any physical or cognitive impairment, and signed a consent form which was approved by the Institutional Review Board of the University of Texas at Austin (UT IRB # STUDY00000287). The purpose of this experiment was to evaluate accuracy of needle force identification from the participants, who received feedback through the different modalities described in Section IV-A.

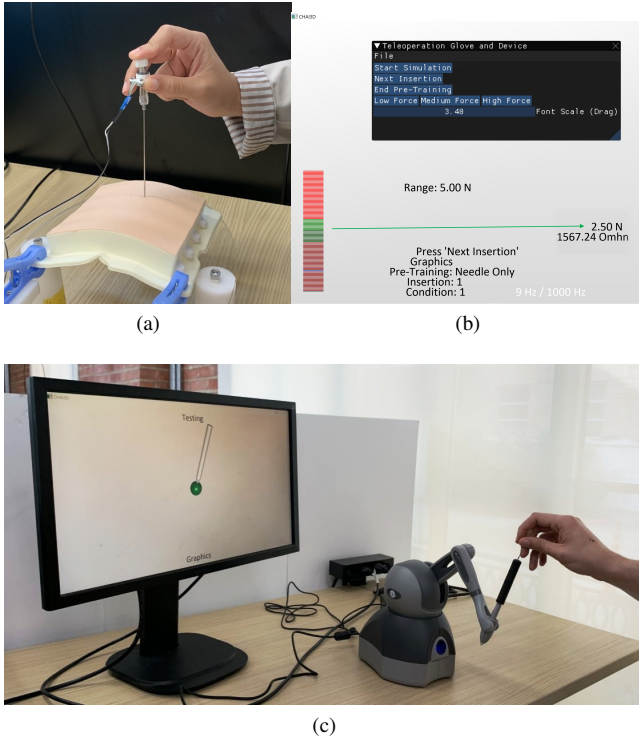


Fig. 5: Experimental Setup. (a) Trainee workspace: experimenter inserts needle into chest pad, (b) Graphical display experimenter uses to gauge force and carry out simulation, (c) Mentor workspace: subject examines graphic and force feedback

Needle force was examined at three distinct levels: low (2.5 N), medium (5 N), and high (10 N). These values were determined by C.P., who is an trauma surgeon at UT Southwestern and expert in needle decompression (over 100 cases) through a pilot study. During this pilot study the instrumented needle was inserted into a standard chest pad simulator with "low", "medium", and "high" forces, where "medium" indicates an appropriate level of force during insertion, "low" would thus be less than necessary (not enough to enter the pleural space), and "high" would be more than necessary (signaling contact with a rib and risk of damaging internal organs).

The main experiment was conducted over the course of one week. Each day, prior to starting the experiment, the force sensor was calibrated to ensure good force accuracy.

The experiment was composed of six blocks. First, in the *pre-training* block, subjects became familiar with the sensation of inserting a needle into a standard chest drain pad. The subject was instructed to push the needle with their index finger while the thumb and middle finger keep the needle in a stable position (Fig. 5a) while generating a particular level of force (low, medium, or high) by reaching a target region of a gauge in the graphical display (Fig. 5b).

For the remaining five blocks, the subject handled only the haptic device, acting as if they were a mentor. Their perception of the experimenter performing the needle insertion task was evaluated under the five haptic and graphic display conditions in a randomized order. Each of these blocks was composed of a *training* phase and a *testing* phase. In the *training phase*, the experimenter inserts the needle at each level of force four times, using the gauge to apply and maintain the appropriate amount of force. At each insertion, the experimenter informed the subject which level of force was being applied and the subject was able to explore the feedback environment (i.e., by moving the stylus up and down) in order to better understand how to distinguish the force levels. In the *testing phase*, the experimenter inserted the needle 15 times, with five randomized repetitions for each of the three force-levels in a randomized order. During each insertion, the subject examines the feedback provided by the haptic device and verbalizes the force level (low, medium, or high) they believe is being applied. This level is recorded by the experimenter. After each block, except for pre-training, the subjects completed a NASA-TLX survey [35] to evaluate perceived workload under each condition.

V. RESULTS AND DISCUSSION

Participants were evaluated on their ability to correctly identify the level of force based on the feedback they were provided. Data analysis was performed by authors Y.Z., E.B and A.M.F., who were blind to the conditions they were examining. Figure 6 shows the accuracies for each condition at the different force levels. It can be seen that conditions C1 (graphics and pushing force) and C3 (graphics only) have overall good accuracy, while C2 (graphics and pulling) shows a worse performance of three conditions with graphic feedback. The haptic only conditions (C4 and C5) show a markedly higher error for discrimination between the medium and high levels of force.

This difference in performance is confirmed by Figure 7, which shows a boxplot of the overall accuracy for each condition. Median accuracies are 100.0%, 86.6%, 93.3%, 66.7% and 73.3% for conditions C1 to C5. It can be seen that C1 has the highest median, followed by C3 and C2. C1 also shows the smallest variance.

This experiment was a repeated measure design with strongly non-normal data for some conditions (Shapiro-Wilk yielded $p < 0.000238$ and $p < 0.000380$ for conditions C1 and C3). For this reason we used a Friedman test, which showed that the difference in accuracy was statistically significant for the different conditions ($\chi^2(4) = 31.9$, $p = 0.00000201$, effect size Kendall's $W = 0.532$). Pairwise Wilcoxon signed rank test between groups (with Holm

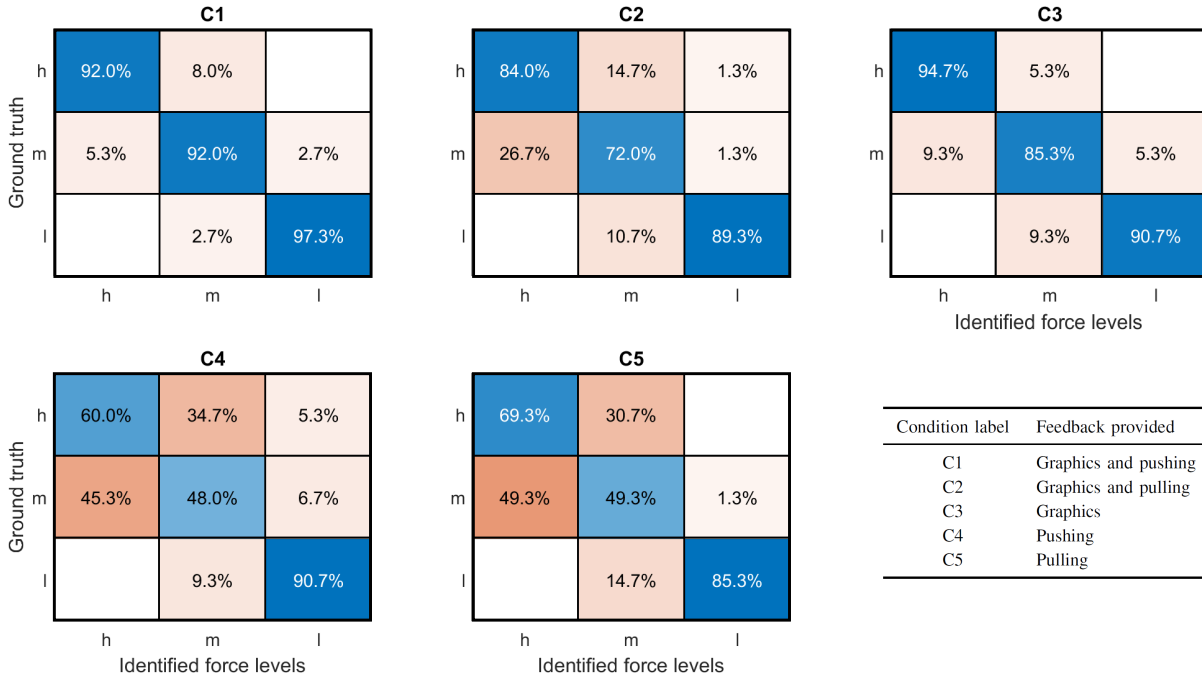


Fig. 6: Accuracy for each condition

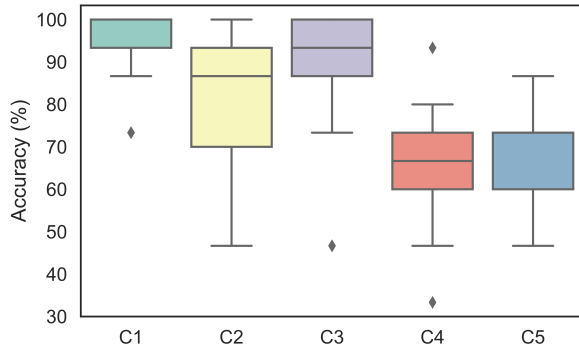


Fig. 7: Overall accuracy boxplot

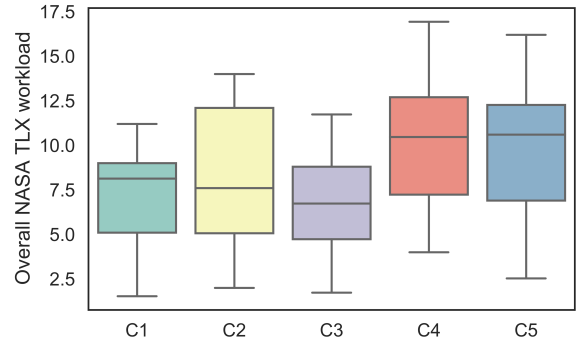


Fig. 8: Workload from the NASA-TLX

correction) revealed statistically significant differences in accuracy between the following pairs: C1 and C4 ($p = 0.024$), C1 and C5 ($p = 0.024$), C3 and C4 ($p = 0.04$), and C3 and C5 ($p = 0.024$). Significance at the 10% level was obtained for Holm-corrected p-values for pairs C1 and C2 ($p = 0.073$), and C2 and C3 ($p = 0.073$).

Figure 8 shows boxplots for the overall NASA-TLX workload. Median values were 8.1, 7.6, 6.7, 10.5 and 10.6 for conditions C1 to C5. A Friedman test showed significant difference between the five conditions ($\chi^2(4) = 11.5$, $p = 0.0213$, effect size Kendall's $W = 0.192$), with pairwise Wilcoxon signed rank tests between groups (Holm corrected) revealing statistically significant differences in perceived workload between C3 and C4 ($p = 0.015$), and the difference between C1 and C4 being marginally significant ($p = 0.081$).

Condition C1 (graphics and pushing haptics) yielded the best performance in terms of accuracy, while C3 (graphics only) yielded the lowest perceived NASA-TLX workload, although both differences between C1 and C3 were not

statistically significant. C2 has worse performance than both C1 and C3 when it comes to accuracy, although it is better than the haptic only conditions C4 and C5. It also has a slightly lower perceived workload than C1. Overall, it seems that the visual feedback was very helpful in discriminating force differences, but it showed indication of working even better when paired with the pushing haptic feedback in condition C1. Although the difference in performance between C1 and C3 was not statistically significant, because C1 showed an overall accuracy close to 100%, with no participant performing worse than 73.3%, we will be using this condition for force feedback in future work.

Interestingly, half of the participants were 100% accurate in discriminating forces under condition C1. Given the sensitive nature of our target application, we would want to reach a target accuracy as close as possible to 100% for all participants. In order to investigate possible explanations for why some participants did worse than others in this experiment, we looked at the position data as measured from

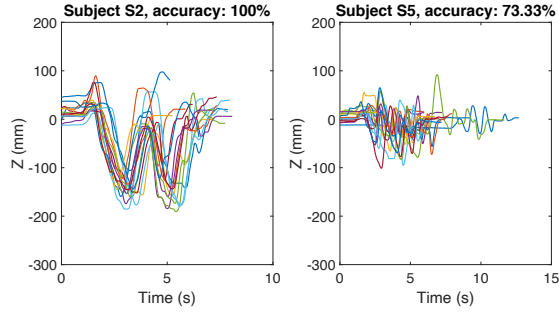


Fig. 9: Mentor movement in the Z direction for two participants under condition C1: graphics with pushing haptic feedback.

the haptic device, specifically the vertical motion. Figure 9 shows an overview of movement for participant S2, who scored 100% under C1, and participant S5, who scored 73.3% (the lowest value recorded). It can be noted that S2 has a larger movement in the Z coordinate, indicating that the participant used more exploratory movement to evaluate the trainee's applied force. S5 on the other hand moved much less.

Similar differences are observed in other participants. More formally, if we define as $\Delta z_{i,j}$ the difference between the maximum and minimum value of the zeta coordinate for trial number i for participant j , we can calculate the following measure of the average range of movement for each participant:

$$\Delta \bar{z}_j = \frac{1}{n_t} \sum_{i=1}^{n_t} \Delta z_{i,j} \quad (1)$$

where n_t is the number of trials for each participant (15 in this case). The results of this analysis are shown in Figure 10. There appears to be a trend where mean movement on the Z

axis which is lower than 150 mm correlates to worse accuracy in the identification of levels of force for condition C1 (graphics and pushing). This is also present for C3 (graphics only), albeit with two participants straying off strongly from this pattern. This particular pattern it is not observed for the other conditions. While participants were not instructed on a specific strategy for exploration of the haptic feedback in this experiment, this suggests that exploratory movements can be helpful with increasing accuracy and should be part of the future telementoring platform. Of course, in our envisioned application one must take care not to confuse exploratory movements with insertion/extraction directions to the trainee, which motivates the need to associate a trigger for the mentor to decide when directionality cues should be displayed to the trainee using a button on the haptic device, as described in Section III-B.

VI. CONCLUSIONS

In this work we presented the design of a telementoring system for needle insertion tasks, composed of two sub-systems: a force sensing interface plus a haptic feedback element for the trainee, and a haptic interface plus trainee force visualization for the mentor. We tested five different combinations of visual and haptic feedback to deliver information on the needle insertion force to the mentor and found that a combination of visual feedback and force feedback (C1) delivered against the hand of the mentor (i.e., on the positive local Z axis of the device end-effector) worked best, with a median accuracy of 100%. Condition 3, visual feedback only, was also a strong feedback condition with a median accuracy of 93.3% and a lower perceived workload as classified by a NASA-TLX survey. The remaining three conditions were less effective in the force identification experiment. Further analysis of movements performed by participants during the experiment showed indication that performance in the C1

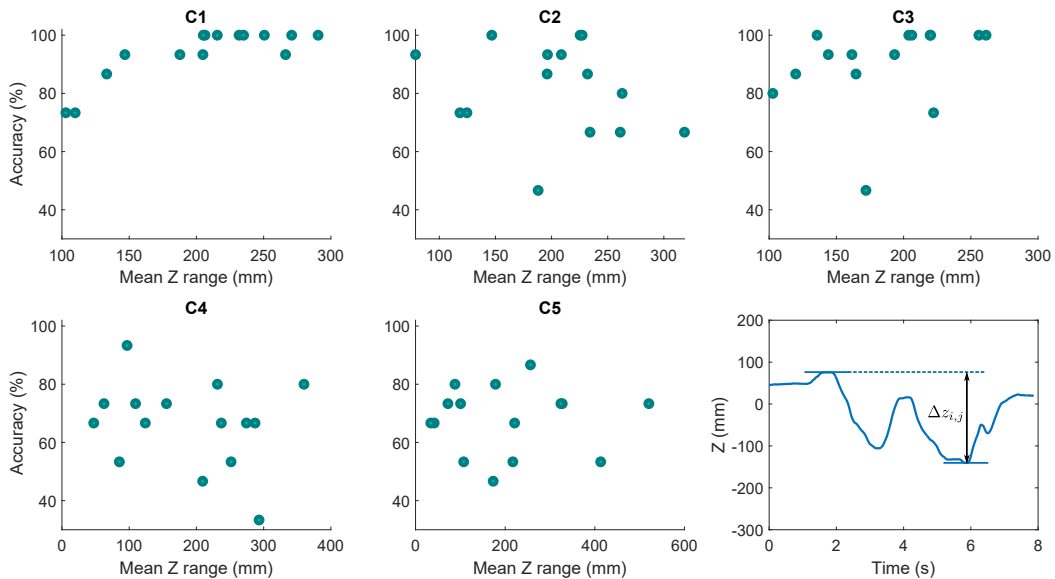


Fig. 10: Scatter plots of the average movement on the Z coordinate for each participant against accuracy, for each condition. The last subfigure shows a sample trial with its Z range excursion.

condition can be improved if the mentor employs more exploratory movements. To our knowledge, this is the first evaluation of a mentor-side display in telementoring systems that evaluated both haptic and graphic feedback.

Although no statistical difference was observed between C1 and C3, the almost perfect performance observed with combined visual and haptic feedback point to this modality as the best choice. Future studies on the haptic feedback gains might improve user perception of workload. One limitation of this work is that we used data from a single surgeon to evaluate the levels of force: future work will look at refining this result with multiple surgeons, as well as evaluating performance of the trainees when guided by a remote mentor, using our haptic telementoring system. These studies will pave the path towards the deployment of a haptic telementoring system to train needle decompression tasks in both traditional hospital and pre-hospital settings.

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