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Cartesian Space Vibrotactile Cues Outperform Tool Space Cues when Moving from 2D to 3D Needle Insertion Task

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***Abstract*— Percutaneous needle insertion can be a life-saving procedure in trauma patients. Incorrect needle placement can generate greater patient morbidity, potentially leading to severe complications and even death. Because of the fact that it occurs in emergency situations, this procedure often has to be performed by individuals who are not experienced in its execution, with a greater potential for mistakes. To address this, in a previous conference publication we introduced a vibrotactile sleeve to guide users in this task along two degrees of freedom. In this paper we extend this approach to three degrees of freedom with a new design, and evaluate the outcome of three different cue delivery strategies (Tool, Cartesian and Joint). Results show accuracy greater than 95% in discriminating between nine possible directions on the Cartesian modality. In addition to being used for the development of needle insertion guidance systems, with first responders benefiting from remote expert guidance, the sleeve could also inform training methods for new medical practitioners.**

I. Introduction

Despite technological advances in medicine, trauma remains one of the most common causes of death and disability in the United States [1]. While the severity of the injury itself obviously plays an important role in the final outcome, time to patient intervention and coordination of pre-hospital and hospital providers are two crucial aspects that can be leveraged. As pre-hospital providers improve their ability to intubate patients and control hemorrhage [2] and mature level trauma centers continue delivering evidence-based, efficient care [3], training continues to play an important role.

The traditional mantra of ‘see one, do one, teach one’, where the junior resident first observes several cases, then does one under supervision and finally achieves competency to teach [4], [5], has been negatively affected by a reduction in trainee work hours, which are now capped to 80 hours despite a subjective decrease in clinical performance [6]. Furthermore, fundamental shifts in the kinds of surgical treatments provided to trauma victims, due to technological advances in imaging and other non-operative techniques, have significantly decreased exposure of trauma surgical trainees to more complex cases [7], [8]. Since human error remains an important cause of deaths that could otherwise have been prevented [9], better tools for training and assistance during emergency procedures are highly desirable.

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Fig. 1: 3D Vibrotactile Sleeve.

There are many examples in the literature on delivering immersive training experiences through haptics and virtual reality [10], including needle insertion trainers [11], [12], laparoscopic trainers [13], and catheter insertion simulators [14]. Indeed, robotic and haptics systems can enhance performance when deployed as a guidance and assistive tool that keeps the human in the loop and in control of high level decisions [15], [16], [17]. Much of the focus in telemedicine has been devoted to development of telerobotic systems capable of remote surgery [18]. A recent review of current applications in surgical telementoring found that although teleconferencing is a wide spread and accepted practice, the use of more sophisticated tools such as robots and virtual reality is still relatively unexplored [19]. Authors noted that the major drawback in telerobotic systems is their high complexity and cost when compared to simple telementoring. With this in mind, it appears that there is a need for technology-assisted telementoring that is simple and cost effective.

We aim to address this challenge with a vibrotactile sleeve that can be used to guide a first responder according to input from an expert, as well as for training. While in [20] we presented a preliminary version of this sleeve that could deliver cues on two degrees of freedom, in this work we extend it to three dimensions and evaluate the accuracy of direction classification for different types of cues in a user study. In the next sections we will motivate the choice of adding a third degree of freedom, describe the cue delivery system and present the user study.

II. Problem Statement

In this section, we present some general considerations on the needle insertion task which were used as guidance for the design of the sleeve. While there is a large body of literature on needle insertion modeling that aims to estimate interaction forces from sensor measurements [21], [22], as our goal

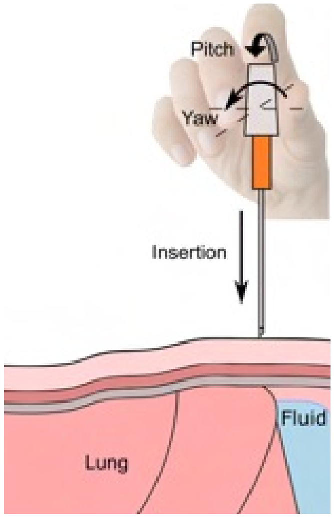


Fig. 2: Overview of a needle insertion task (in this case needle aspiration for pneumothorax decompression.

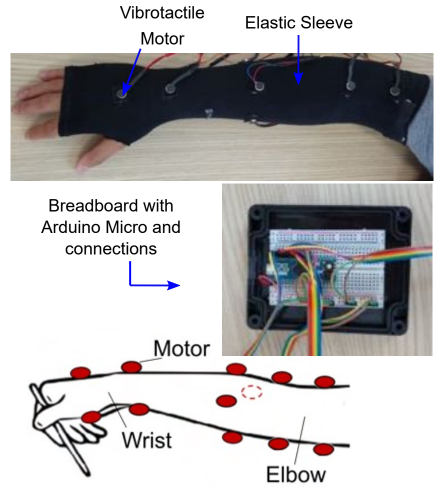


Fig. 3: Hardware and vibrotactile motors placement.

is creating an assistive system, we will here present only general considerations on kinematics, and focus on manual needle insertion.

Figure 2 shows an example of a needle insertion task, namely needle aspiration to remove fluid from a lung. Needle insertion is a task that presents some similarities with the use of other simple tools such as pens and brushes. While moving as needed in space, just like when using those other tools, one has to control three degrees of freedom of positioning in a cartesian space, as well as three degrees of freedom of orientation, for a total of six degrees of freedom. For medical needle insertion, once the insertion location is chosen the task is further constrained by the patient tissue resulting in one translational (insertion), and two rotational degrees of freedom (pitch and yaw, with roll being unimportant when using a symmetric needle).

In our previously published work [20], we presented a cue delivery strategy that aimed to guide the user on the insertion and pitch degrees of freedom by using a sleeve with vibrotactile motors. We considered three distinct activation patterns for the motors corresponding to cues in Tool, Joint, and Cartesian space. This preliminary work showed that tool space cues were associated with better performance in a 2D needle insertion task. In this paper, we investigate if these results extend to the 3D case by modifying our prior vibrotactile sleeve to include a third degree of freedom (i.e., yaw) to each of the three vibrotactile activation strategies. We conduct a human user study to investigate the effects of these cues on performance in a simulated 3D needle insertion task.

III. Tactile Guidance Sleeve

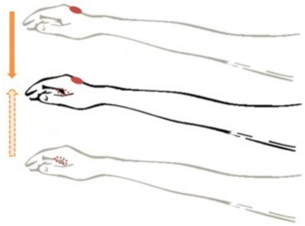
The tactile guidance sleeve was created using an elastic compression sleeve and twelve vibrotactile motors (ROB-08449, Sparkfun). Velcro squares were placed on target locations on the compression sleeve, and matching velcro patches were attached to the bottom of each of the motors. The motors were connected to ribbon cable running along the sleeve, which was in turn connected to the ports on the Arduino Micro used to control the motors. Figure 3 shows the sleeve with motors on it, the breadboard with the Arduino and connections for the motors and placement on the arm for the twelve vibrotactile motors.

Five motors were placed in a line above the arm, another five in a line below, and two motors were on each side on the forearm. The four motors in the wrist area were placed in such a way that two of them would be proximal with respect to the wrist (above and below the arm respectively), while the other two would be distal with respect to the wrist and lay on the dorsal and palmar side of the hand. The four motors around the elbow were placed similarly to have a pair before, and a pair after the elbow joint.

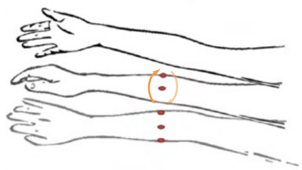
With each of the motors costing around \$2 (\$24 for twelve of them), the Arduino costing \$18 and the sleeve \$5, the total cost of the materials required to put together the sleeve was less than \$50, making it a low cost device for medical guidance and training applications.

IV. Design of Vibrotactile Cues for Movement

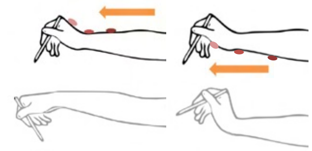
In the previous section, we described the physical realization of the sleeve and motor placement. Here we will show how we leverage this placement to deliver cues. We considered three pattern systems for the activation of the motors: (i) *Tool* space, where directions are given in terms of local translation and rotation of the tool; (ii) *Cartesian* space, where movement directions are delivered based on target movement of the tip of the needle; and (iii) *Joint* space, where joint angles of the user's arm are controlled directly, with the tool modality appearing to be the most effective. Cues for elementary movements along individual degrees of freedom are delivered as illustrated in Figure 4, and compound movements are elicited as a sequence of elementary movements. Two basic mechanisms are used to deliver cues in all modalities: individual activations of motors which simulate a ”push” being delivered to the user, and sequential activations in a line that elicit a saltation effect.



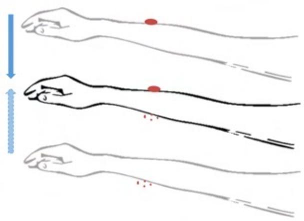
(a) Tool Space Insertion/Extraction.



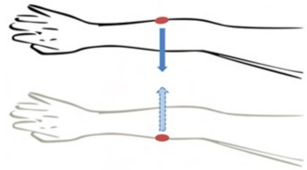
(b) Tool Space Yaw.



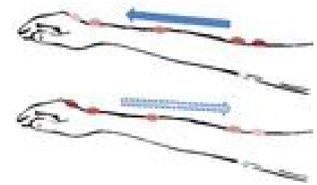
(c) Tool Space Pitch.



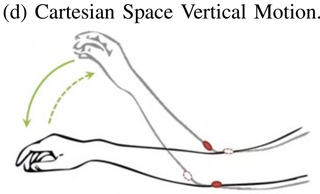
(d) Cartesian Space Vertical Motion.



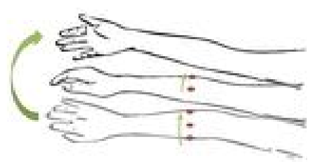
(e) Cartesian Space Lateral Motion.



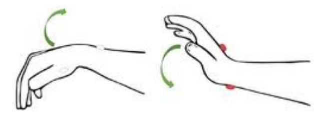
(f) Cartesian Forward/Backward Motion.



(g) Joint Space Elbow Extension/Flexion.



(h) Joint Space Wrist Rotation.



(i) Joint Space Wrist Flexion/Extension.

Fig. 4: Relationship between vibrotactile cues and desired movements for (a) tool space insertion (d) and rotation, (b) Cartesian space insertion and (e) lateral motion, and (c) joint space insertion and (f) wrist rotation.

Tool space cues determine the rotation of the needle directly in terms of yaw by eliciting a saltation effect around the forearm (Fig. 4b), pitch by sequential activation of motors above and below the distal portion of the forearm (Fig. 4c), and insertion/extraction with a single activation of a motor above or below the hand (Fig. 4a).

Cartesian space cues elicit a left/right lateral movement with single activation of a motor on the each side of the forearm respectively (Fig. 4e), a forward/backward movement with a sequential activation of motors above the arm (Fig. 4f) and an insertion/extraction movement with a single activation above or below the forearm (Fig. 4d). It is worth pointing out that these translations are meant to apply to the tip of the needle, rather than just the arm of the user (otherwise it would be impossible to use this system to rotate the needle at the correct angle).

Finally, Joint space cues direct the user to rotate their wrist around the forearm axis through a sequence of activation around the forearm (Fig. 4h), elicit a rotation around the wrist axis with a paired activation of pairs of motors on the hand and wrist (Fig. 4i) and command an extension/flexion movement for insertion/extraction of the needle through paired activation of motors around the elbow joint (Fig. 4g).

V. Experimental Methods

We ran a user study with twelve participants (age 22.8 ± 3.2, four females). All participants were right handed and did not suffer from any physical or cognitive impairment, nor any pathology that could affect tactile sensitivity of the forearm. The methods and procedures described in this paper were carried out in accordance with the recommendations of the Institutional Review Board of University of Texas at Austin, with written informed consent obtained from all subjects.

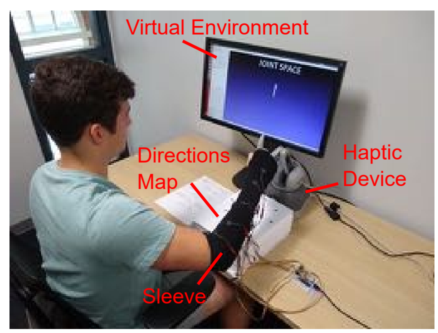


Fig. 5: Experimental setup

Participants wore the sleeve on their right arm while using a haptic device (Geomagic Touch, 3D systems) in a virtual environment created in C++, and relying on Chai3D and Qt for haptic rendering and GUI elements, respectively (Fig. 5 shows the experimental setup). Before each trial, participants assumed the same starting position and orientation, as tracked by the haptic device and displayed by the virtual environment. At the end of each trial participants pressed a button on the haptic device stylus to move to the next trial. Participants were encouraged to take breaks whenever they felt it necessary, and there were mandated one minute breaks between different phases of the study. The experiment took approximately one hour and a half for each participant.

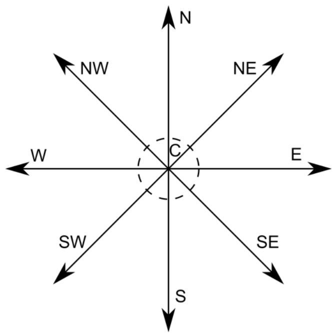


Fig. 6: Visualization of target directions

The study consisted of three parts. The first part consisted of a *Pre-Training* phase where participants were introduced to the study, signed the consent form and were instructed on how the three cue delivery patterns (tool, cartesian and joint) work. A printout of Figure 4 was used as a guide. Participants then started interacting with the haptic device and virtual environment, with elementary cues from each modality being provided to them. The experimenter worked with participants in this phase to ensure that the mechanism of delivery of each individual cue was clear and that no mistakes were made because of misunderstanding related to the meaning of the cues.

Fig. 7: 3D visualization of the target direction during training.

The second step was a *Training* phase where participants were exposed to compound cues aimed at guiding them towards one of nine possible directions, with one being a straight line down from the starting position and the remaining eight being diagonal lines aiming down and towards all possible cardinal directions (North, North-East, East etc.). A visualization of these directions is shown in Figure 6. An unlabeled version of this image was printed on a letter sized paper which was taped over a box, and participants were instructed to place the end effector of the haptic device in the center of the circle for direction C, and on each arrow for all other directions. During this training phase participants were instructed to follow the haptic cues towards what they thought was the desired direction, and were then provided a 3D visualization of the actual desired direction. This was repeated two times for each direction to help them familiarize with the compound cues, and was divided in three blocks of trials, one for each cue delivery modality. The order of the cue modalities were randomized for each subject.

The third and final step was the *Testing* phase where participants were provided with a sequence of randomized cues in which each direction appeared three times (for a total of 27 trials for each cue delivery modality). This phase did not have any 3D visualization for the target direction but was otherwise identical to the previous training phase. Participants were evaluated on accuracy during this phase in terms of successful identification of the target direction based on the haptic feedback.

At the end of the experiments participants were filled a NASA-TLX survey [23] to evaluate perceived workload while using each modality.

VI. Results and Discussion

Evaluation of accuracy was performed on the testing phase. Similarly to what was done in [20], we used the measured kinematics from the haptic device to compare stylus movement with the target direction. The line connecting the starting position of the end effector with its position at the end of the trial was considered, and its angle with each of the possible directions computed. The direction for which this angle was smallest was taken as the one chosen by the participant for this trial and compared with the desired one.

Figure 8 shows an overview of the outcome for one participant (S11). Each circle represents the final position for one trial, and is colored to match the target direction. It can be seen that for this participant the Cartesian modality exhibits the highest accuracy. This is also observed in the remaining participants, leading to the results shown in Figures 9, where the overall accuracy by cue for each modality is shown and the Cartesian modality shows the best performance. Figure 10 gives an overview of the overall accuracy further confirming a better performance from the Cartesian patterns when compared to the other modalities (medians were 96.3% for Cartesian, 77.8% for Tool and 67.9% for Joint).

This experiment was a repeated measure design and, because the overall accuracy in the Cartesian modality was skewed towards 100%, included strongly non-normal data (as shown by a Shapiro-Wilk test which yielded $p < 0.0007$ for the Cartesian modality). For this reason we used a Friedman test, which showed that accuracy was statistically significantly different for the different cue delivery modalities ($\chi^2(2) = 20.0$, $p = 0.0000464$, effect size Kendall's $W = 0.832$). Pairwise Wilcoxon signed rank test between groups (with Holm correction) revealed statistically significant differences in accuracy between Cartesian and Joint ($p = 0.008$); Cartesian and Tool ($p = 0.008$); and Tool and Joint ($p = 0.045$).

Figure 11 shows boxplots for the overall workload as measured by the NASA-TLX survey (medians were 4.9 for Cartesian, 8.6 for Tool and 13.2 for Joint). A Friedman test showed a significant difference between cue delivery modalities (($\chi^2(2) = 19.5$, $p = 0.0000583$, Kendall's $W = 0.812$), and pairwise Wilcoxon signed rank tests between groups (with Holm correction) revealed statistically significant differences in perceived workload between Cartesian and Joint

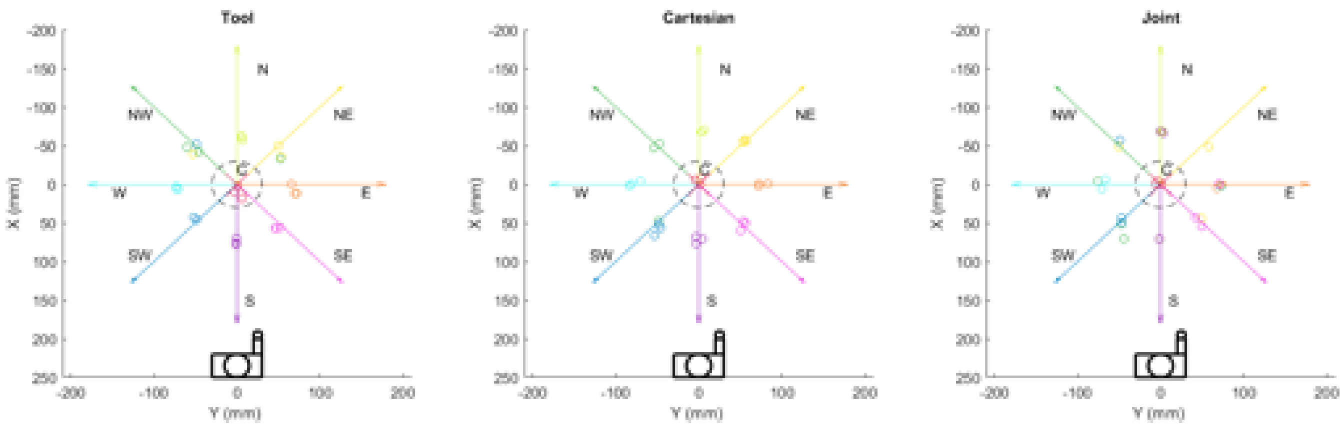
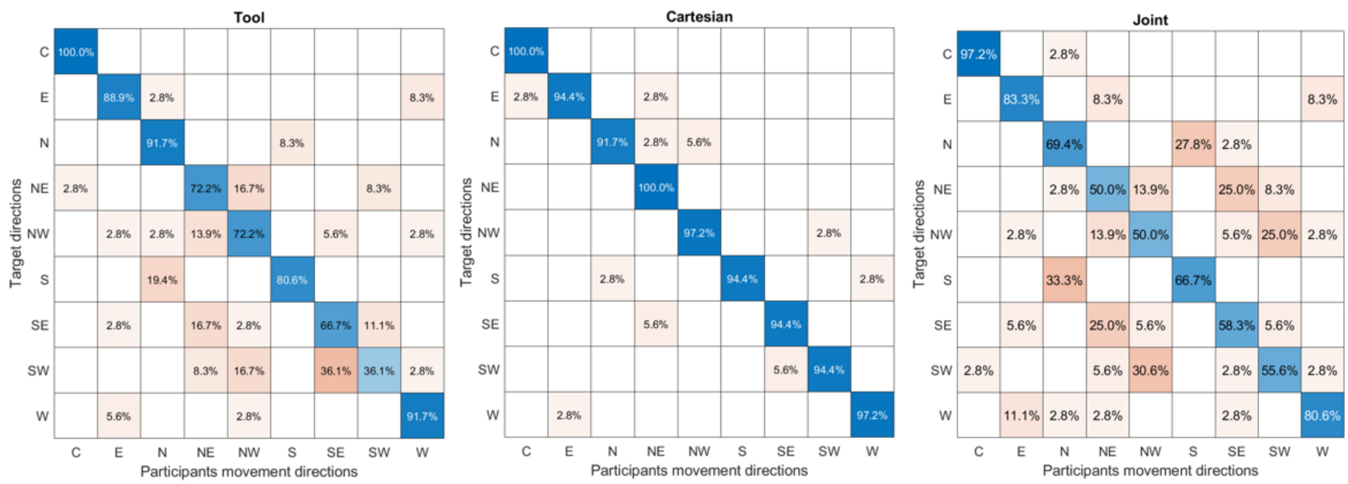


Fig. 8: Overview of testing trial results for a representative subject (S11). The circles represent the final position of the end effector.



(a) (b) (c)

Fig. 9: Overall accuracy for each cue modality.

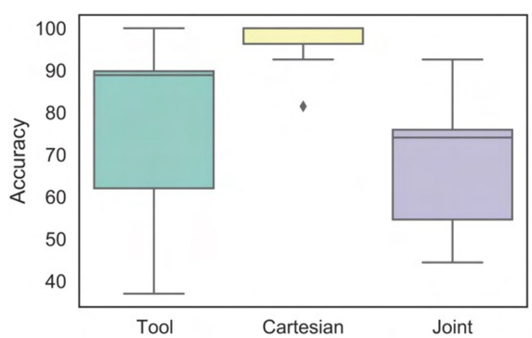


Fig. 10: Overall accuracy box plot.

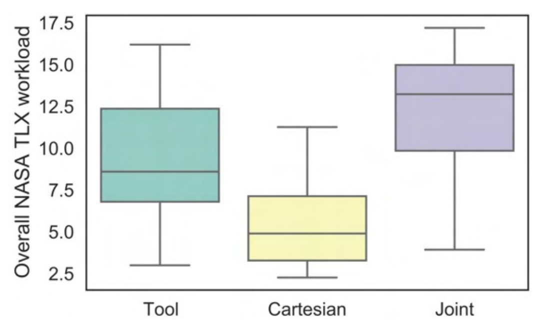


Fig. 11: Workload from the NASA-TLX.

($p = 0.000488$); Cartesian and Tool ($p = 0.000488$); and Tool and Joint ($p = 0.034$).

The Cartesian modality appears to yield better accuracy, as well as a smaller perceived workload. This is in contrast with the results observed for the 2D case in [20], where the Tool cue delivery approach showed better performance. A possible explanation for this could be found in Figure 9, and can be visualized more clearly in the interaction plot shown in Figure 12. Participants did show good performance on Tool for the discrimination between W and E directions, but had a harder time discriminating when these directions were superimposed to S (accuracy for SE and SW is 66.7% and 36.1% respectively). Similar, although less noticeable changes of errors can be seen in the NW/NE comparison. Interestingly, the Tool modality also caused participants to commit a relatively high error when exposed to the S cue, which was mistakenly identified as a N cue. These directions corresponded to a pure pitch rotation, which is the additional

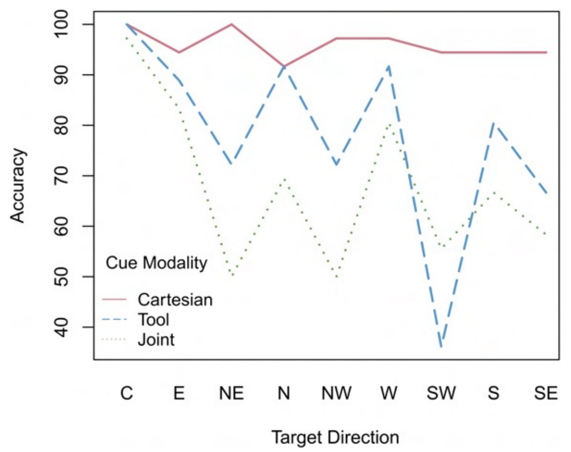


Fig. 12: Interaction plot of the combined effect on accuracy of target direction and cue modality.

degree of freedom that was introduced with respect to [20]. The Tool modality also showed the greatest variability in performance across participants (Fig. 10).

VII. Conclusion

In this paper, we present a vibrotactile sleeve that can deliver directional cues across three degrees of freedom, for guidance in a needle insertion task. We evaluated its effectiveness with a user study where participants had to move the stick of a haptic device according to cues from the sleeve, comparing three different pattern systems for cue delivery: a Tool modality, where the vibrating motors direct the pose of the tool directly; a Cartesian modality, which directs movement of the needle tip; and a Joint modality, which directs individual joints on the user's arm.

Results show greater accuracy for the Cartesian approach (median 96.3% versus 77.8% for Tool and 67.9% for the Joint approach), as well as a lower perceived workload as quantified by the NASA-TLX survey. This contrasts results from our previous work on a preliminary 2D design where a similar Tool modality was found to work best. This could be explained by the added degree of freedom, as suggested by closer examination of errors on the individual directions of movement that we evaluated. Interestingly, the Joint modality was the worst for both this work and the previous work. Together, these results suggest the addition of a tool and the level of complexity for the tool and task objectives play a significant role in the design of intuitive and natural guidance cues for human movement. Future work will focus on integrating this sleeve with a sensing system to better share task-based information (e.g., applied forces) with a remote mentor.

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