# Evaluation of Tactile Guidance Cue Mappings for Emergency Percutaneous Needle Insertion

Sukanya Basu*[1], Jeremy Tsai*[2], and Ann Majewicz[3],[4]

***Abstract*— In severe trauma cases, rare but fatal conditions may quickly arise, requiring immediate percutaneous needle insertion to save the patient. As there is no time to wait for experts, inexperienced individuals are often required to perform these procedures, often leading to complications. We propose to design a novel vibrotacile sleeve to guide users through this task. While realization of a robust closed-loop guidance system is far from complete, we begin this project by identifying and evaluating three major guidance cue mappings that could be used for our sleeve: (1) tool space (guiding needle orientation and insertion), (2) Cartesian space (guiding desired needle tip), and (3) joint space (guiding user elbow and wrist angles). In this paper, we aim to determine which of these mappings have the best performance in a simulated needle insertion task. We developed an adjustable sleeve consisting of a stretchable fabric with vibrotactile motors, affixed using hook-and-loop material. In a human subject study, we evaluated the effectiveness of these cues to elicit a series of desired movements (up, down, lateral motion, rotation, diagonal movement) by tracking the subject movements as they interfaced with a haptic device. We found that tool space guidance mappings lead to significantly lower normalized direction error for both up/down and diagonal movements (p value <0.0001). Users also rated tool space as the easiest mapping (1.87/5, SD= 0.75) and found that diagonal movements were the most difficult cues to understand.**

## I. Introduction

The difference between life and death can be just a matter of minutes for trauma patients with a traumatic airway obstruction or a tension pneumothorax. This type of trauma is often the result of a severe chest injury which can lead to lung compression and heart failure. As reported by Coats et al., 59% of trauma patients requiring heliotransport developed a tension pneumothorax and required immediate needle-based decompression [1]. This procedure requires extreme precision and care to avoid complications such as cardiac tamponade, hemorrhages, and other morbidities [2]. First-Responders are often ill-equipped and have inadequate training necessary to diagnose and successfully treat these conditions.

Patient simulators have often been used to train medical students and emergency medical professionals to perform procedures like percutaneous needle insertion for tension pneumothorax; however, they are hindered by limited realism and the costs of simulator-based educational programs, equipment, and personnel [3] [4]. Moreover, these programs have limited use in emergency scenarios, as there is no guarantee that trained medical professionals will be available at the site of the trauma. Over the years, many robotic systems have been developed for percutaneous needle insertion [5], [6], [7], [8] (see review in [9]); however, none of these systems are feasible, to date, in an emergency scenario where patient position and orientation cannot be controlled, and significant setup or deployment time could be fatal.

Thus, we aim instead to develop a vibrotactile guidance sleeve to assist the human user with performing a percutaneous needle insertion for emergency scenarios. Our first objective is to determine which vibrotacile guidance cues are able to accurately and intuitively guide the human user to perform a desired movement. We evaluate the accuracy and difficulty of three different vibrotacile guidance mappings used to elicit these movements: (1) tool space, (2) Cartesian space, and (3) joint space (Fig. 1). In tool space, the vibrotacile cues guide how the user should hold and translate the needle. In Cartesian space, the vibrotacile cues define the desired movement of the needle tip, and finally, in joint space, the vibrotacile cues define user limb movements (e.g., wrist and elbow rotation) during the needle insertion task. We developed a tactile guidance sleeve test-bed and vibrotacile cue sequences to evaluate these mappings.

The long term goal of this project is the creation of a low-cost, publicly available emergency needle decompression kit for public transportation vehicles and large public gathering spaces, similar to Automated External Defibrillator systems (AEDs). When integrated with appropriate vision

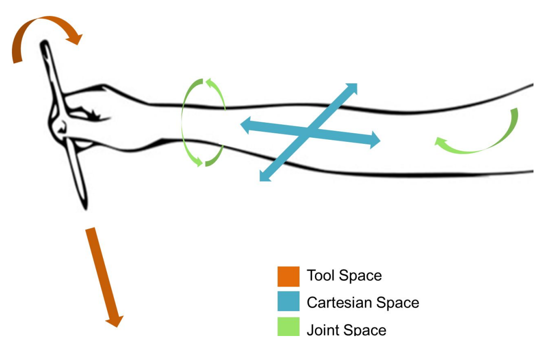


Fig. 1: Percutaneous needle insertion guidance cues. Cues evaluated in this paper include: tool space cues(orange), Cartesian space cues(blue), and joint space cues(green).

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or sensor-based trajectory planning algorithms, our sleeve could provide intuitive movement cues to assist a human user during percutaneous needle insertion into the chest, potentially providing a life-saving benefit to trauma victims. Beyond medical emergencies, this sleeve could be useful for guidance or training in prostate brachytherapy [10], knee arthroplasty [11], fluid drainage [12], and nephrostomy [13], particularly in mid- to low-income countries where medical training is limited [14], [15]. Due to the ubiquitous nature of needle insertion, this assistive device could have far reaching impacts in surgery and interventional care.

## II. Vibrotactile Cues for Guidance and Feedback

Vibrotactile cues have often been used in the field of medical robotics to provide additional knowledge to the human operator. For example, vibration feedback can be used to improve force perception in laparoscopic surgery [16] and robotic surgery [17]. It can also provide valuable information regarding the desired orientation or position of surgical tools. In one study, vibration feedback improved performance over a visual feedback in terms of guiding the orientation of a steerable needle. [18]. This is likely due to the fact that vibrotacile feedback is able to reduce mental workload by substituting haptic cues for ones typically required in the visual feedback channel, particularly in complex navigation tasks, such as driving navigation [19].

Tactile cues have often been used to guide desired spatial movements and have applications such as motion-guidance for individuals suffering from stroke or visual impairment, [20], [21], yoga posture [22], teacher-demonstrated motor tasks [23], and instrument learning [24]. These systems typically require some sort of external camera or sensor system to accurately model the position and orientation of the human user in space in order to provide appropriate guidance cues. Often these tactile cues consist of turning a single vibrotatcile motor 'on' or 'off; however, they may also consist of compound vibration sequences to give the illusion of directionality (e.g., forward, backward, rotation), using the saltation effect [25] [26], [22].

The success of vibrotactile cues in terms of complex navigation and sensory substitution make it a promising choice for guidance of human users during percutaneous needle insertions. To the authors knowledge, this paper is the first to determine exactly which cue mappings are most effective for needle placement and insertion in an unconstrained environment. Recently, a vibrotactile wrist band was developed to guide users performing a brachytherapy task [27].

## III. Tactile Guidance Sleeve

Three major tasks have been identified in 3D percutaneous needle insertion including: (1) 3-DOF placement of the needle tip at the selected entry point, (2) 2-DOF rotation to orient the needle about the entry point, and (3) 1-DOF insertion or retraction along the needle axis [28]. For the purposes of this study, we selected the four primary degrees of freedom which correspond to a 2D needle insertion task, namely 2-DOF placement, 1-DOF rotation, and 1-DOF insertion or retraction. We then identified three plausible "guidance mappings" that could guide a human user to produce movements within the set of possible 2D needle trajectories. Our mappings include (1) tool space, (2) Cartesian space, and (3) joint space (Fig. 2). Tool space mapping is designed to guide the user on how to orient the needle and insert or retract the needle axially. Cartesian space mapping guides the user based on the desired location of the tip of the needle in Cartesian space (x-y motions). The user is free to determine how to best orient the needle to achieve the desired trajectory. Joint space mappings are often used for movement therapy and motor training [27] [29] and guide the rotations of the wrist and elbow. In the sections below, we describe the selected vibrotactile cues for several key 2D needle movement trajectories as well as describe the design of the tactile sleeve.

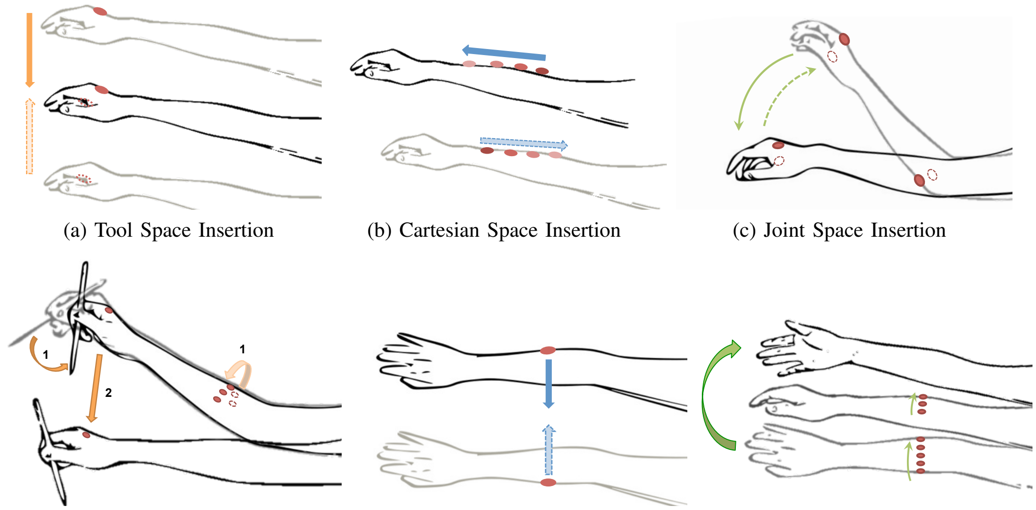
### *A. Vibrotacile Movement Cues*

Within the four degrees of freedom for 2D needle insertion tasks, we selected six primary movement trajectories with which to evaluate the three mappings identified in the section above. The movement trajectories are: (1,2) down and up, (3,4) lateral right/left movements in cartesian space, or right and left rotations in joint and tool space, and (5,6) right and left diagonal movements. In the 2D case, rotation has no meaning in Cartesian space and lateral movements have no meaning in tool or joint space, thus for the purposes of this experiment, we considered lateral movements and rotations to be equivalent one DOF movements which in some way affect the lateral position of the needle tip. Future extension of this work into 3D will allow for more direct correlations between the needle tip movements and guidance cues.

Each of the three mappings requires a different type of guidance cue to signal the desired movement trajectory (Fig. 2). Tool space control requires a rotation cue to change needle orientation and a push/pull cue for insertion. Cartesian space control requires lateral (right or left) pushes or forward, backward, and diagonal strokes (multiple factors in saltation sequence). A single push (i.e., single tactor) was used for left and right cues because a stroke sensation felt more like a rotation as the tactors are not co-planar. Finally, joint control requires sensations corresponding to opening or closing the elbow joint as well as wrist rotation. Diagonal movements in tool space and joint space require a compound movement that first includes a tool or wrist rotation, followed by an insertion cue (i.e., push down or open elbow, respectively).

### *B. Sleeve Design and Tactor Locations*

To implement the movement cues identified in the prior section, we developed a vibrotactile guidance sleeve. The sleeve was designed and sewn out of a soft stretchable material (Lycra), and is similar in form to an athletic compression sleeve. Two sizes of sleeves were made to accommodate different sized subjects. The vibration motors, or tactors, used in this experiment were 10 mm shaftless vibrations motors (310-101.945, Precision Microdrives). The locations



(a) Tool Space Insertion (b) Cartesian Space Insertion (c) Joint Space Insertion

(d) Tool Space Rotation and Insertion (e) Cartesian Space Lateral Motion (f) Wrist Rotation (Tool/Joint Space)

Fig. 2: 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.

and numbers of tactors were chosen based on the desired movement cue sensations. As the locations of the tactors might need to change based on the size and shape of a subjects arm, we used 1/4" hook and loop strips to define the general location for each motor and applied an adhesive hook patch to the bottom of each tactor for easy reconfiguration. On top of each strip was a 0.9 cm diameter vibrotactile motors. The vibrotactile motors were powered and controlled with an Arduino Uno device.

For tool control, tactors on top of the hand and on the palm defined the down/up cues (Fig. 2(a)), and four tactors arranged circumferentially along the top of the forearm defined right and left rotations for both tool and joint control. A combination of these two cues would generate diagonal movements in tool space control (Fig. 2(d)). Four tactors were chosen for the tool and joint space wrist rotation as well as for the up/down stroke in Cartesian space control based on recommendations in the literature to create a compelling saltation effect. This effect, also known as the "cutaneous rabbit" arises from sequentially applied vibrations along the skin [25]. For Cartesian space control, the outermost of the 4 tactors used in rotation were also used for left and right lateral pushes. The Cartesian space diagonal cues, which are described in the following section, employ all the tactors for the Cartesian up/down movement as well as the tactors for the tool and joint space rotation cues. Finally for joint space control, the elbow open and close cue was defined by the tool control tactors on the back of the hand and palm, as well as tactors placed above and below the elbow joint. When the palm tactor and tactor above the elbow are simultaneously energized, the resulting sensation feels like a torque trying to flex the elbow joint. When energized simultaneously, the tactor below and on top of the hand result in a torquing sensation that extends the elbow joint. A total of 12 motors produced these sensations.

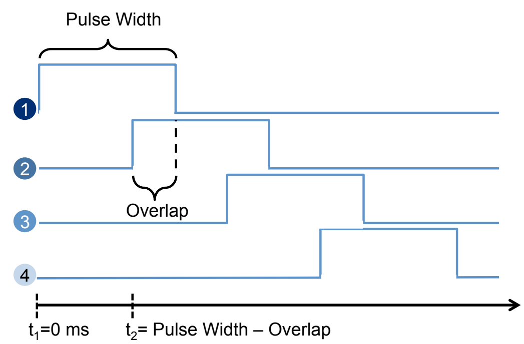



Fig. 3: Saltation pulse sequence. For cues which require a sequence of vibrations to create a saltation effect, the motors were programmed to turn on for a set time (pulse width), and to turn on a set time (pulse width - overlap) after the prior vibration motor was activated. For these experiments the pulse width was 250 miliseconds and the overlap was 35 miliseconds.

### C. *Stroke Cue Implementation*

All stroke cues (rotation, Cartesian down/up, and Cartesian diagonal) were generated using the saltation illusion [25]. The first tactor would turn on and stay on for 250 ms. This time is within ranges known that elicit the saltation illusion [30]. The next tactor turned on before the first tactor turned off with an overlap of 35 ms. The precise timing for this sequence for four motors is shown in Figure 3. To create diagonal stroking cues in Cartesian space, two perpendicular saltation sequences were provided simultaneously, as shown in Figure 4. In tool and joint control, the rotation cue was first applied to ensure proper needle orientation, followed by the corresponding insertion cue for that control space.

## IV. Experimental Study

To evaluate the effectiveness of the different guidance mappings, we used a haptic device (Geomagic Touch, 3D

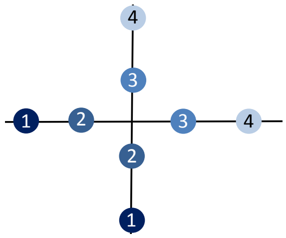



Fig. 4: Cartesian space diagonal cues. For the right and left diagonal cue in Cartesian space, a simultaneous forward and clockwise rotation (right diagonal) or counterclockwise rotation (left diagonal) is given. For both cases, the encircled numbers indicate the order of motor activation to create the diagonal sweeping sensation across the forearm.

systems) and a custom testing environment created with Chai3D and C++. A total of 13 right handed subjects were recruited to participate in this human subjects study, which was approved by the UTD IRB (#14-57). In the experiment, users were randomly presented with vibrotactile cues and their movements of the haptic device along a 2D 30° inclined haptic channel were recorded. The experiment consisted of two parts: (1) a training period to introduce each of the cues to its desired effect through a visual movement cue and (2) a recorded motion study, where the user moves the needle based on the cue provided without visual feedback. For each new trial, in the pre-initialization phase, a starting target defined by a red colored torus is displayed to the user. The tours turns yellow once the user approaches the correct position, and then green when they have reached the desired starting location. Once he or she aligns the stylus of the haptic device with the 30° inclined haptic channel, the green torus will disappear. Post-initialization, the user will be given a new guidance cue and, if still training, will be shown the desired movement trajectory for the simulated needle. After movement the user ended the trail with a button click on the haptic device.

During the training session, visual aid is presented to indicate what kind of movement is expected from each cue.

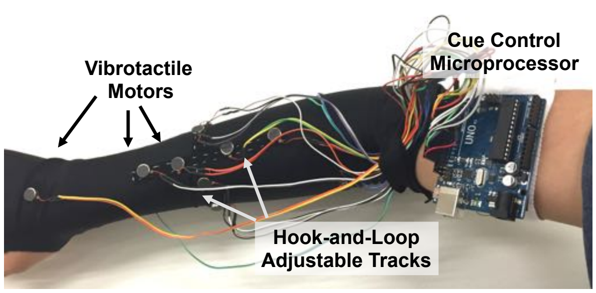



Fig. 5: Vibrotactile sleeve for guidance cue evaluation. The prototype sleeve consists of a stretchable material with hook-and-loop tracks to allow for easy adjustment of the motor locations for each human test subject. Serial communication is used to define cues and an Arduino microprocessor controls the sequencing of the motors for each cue.

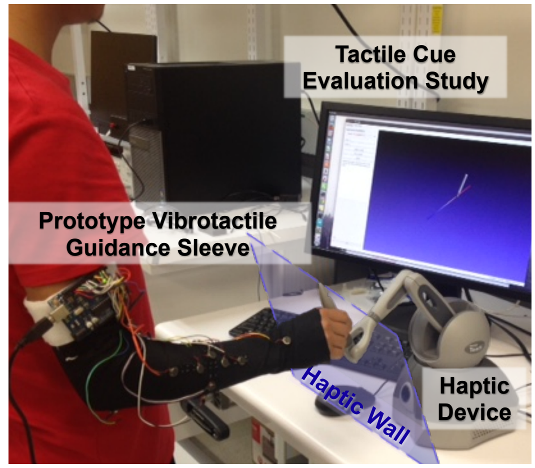


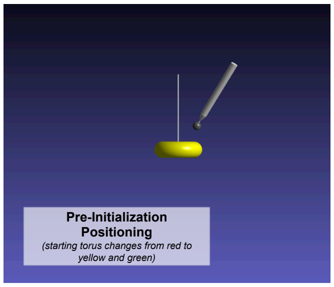

Fig. 6: Experimental setup. Custom code was developed with Chai3D to trigger various guidance cues through serial communication with the Arduino-controlled tactile sleeve while recording user movements during a simulated 2D needle insertion task with a haptic device.

If the desired movement is a rotation, a ghost image of the tool is shown at the correct rotation angle. If the desired movement is a linear trajectory, a blue line is shown to indicates the trajectory of the needle tip during movement. Finally, for diagonal movements, a diagonal line is shown for Cartesian space mappings, and diagonal line with a rotated ghost image of the tool is shown for tool and joint space mappings. Subjects were instructed to wait until they felt a cue before moving. If they did not feel or understand a cue after 15 seconds, they were allowed to advance the trial and it was recorded as a missed trial. Screen captures of the various experimental stages are shown in Figure 7. During training trials, users experienced each of the 6 movements for each of the 3 control modes three times, leading to 36 training trials. During experimental trials, graphics were not shown. The order of control spaces and desired movements were randomized for all subjects. Each of the 6 movements for a given control cue were presented to the user 5 times, leading to a total of 90 experiment trials.

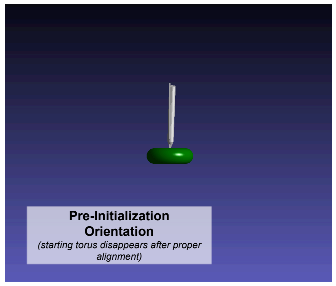
## V. Results and Discussion

Example movements from one subject are shown in Figure 8. Movement traces are color coded based on the desired movement for all mappings. Movement traces for all subjects, color coded by mapping, for particular specific movement types (e.g, Up/Down, Left/Right Diagonal), are shown in Figure 9. As the constraint to the 2D plane was a virtual constraint, the 3D movements are shown. For the most part, all subjects were able to follow the desired needle trajectories with fairly good accuracy.

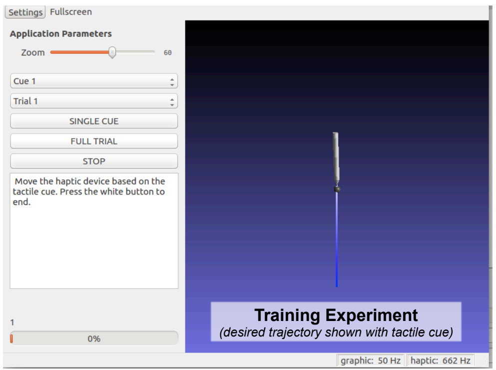
To identify significant differences between different cues, a metric was developed based on the error between the desired trajectory and the position at which the user was farthest away from the start target. We assume that ideal trajectory corresponds to the user is moving in a relatively straight




(a) Pre-Initialization Position




(b) Pre-Initialization Orientation




(c) Post-Initialization, Downward Training Trial

Fig. 7: Screen capture of experiment at various stages including pre-initialization positioning (a), pre-initialization orientation (b), and post-initialization training (c)

line and stops moving as soon as the desired endpoint is reached. The ideal path should be a straight line to that target. Since different users might have a different estimation of where that endpoint should be, we defined a unit vector between the starting point and the point at which the user was farthest away from it. We defined another unit vector along the ideal need path. The Euclidean distance between these two vectors was calculated and normalized across all subjects to create a common metric. As can be seen in Figure 10 which shows the group means and standard deviations of this error across all subjects, the normalized directional error for vertical movements is significantly less for the tool control mode compared to Cartesian and joint control modes. Cartesian space mappings for diagonal movements have more error than the other two mappings for the same movement. These results were found to be significant through a Kruskal Wallis non-parametric analysis of variance test (see Table I). A p-value of less than 0.05 indicates that a group has statistically significant differences; however, we note that due to unequal variance of some data groups, the Kruskal Wallis tests have limited modeling power. To further identify which groups were significantly different from each other, a post-hoc Scheffe Test was performed using the Kruskal Wallis test statistics.

We found that the tool space mapping had less directional error than both Cartesian and joint space control for both up/down and diagonal movements. Furthermore up and right

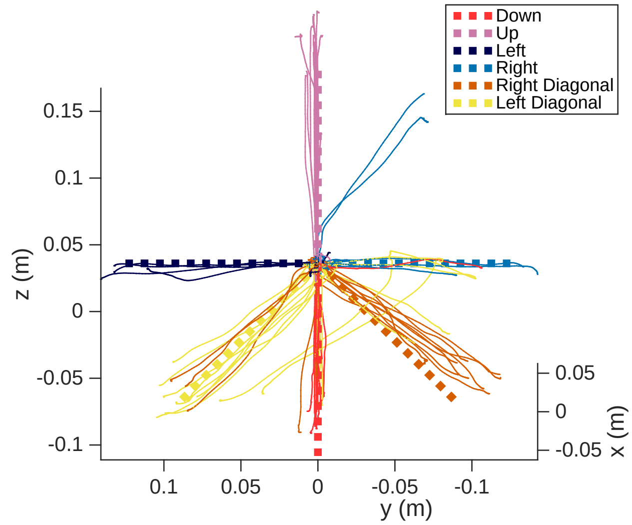



Fig. 8: Example of all movements from a single subject, under all guidance mappings. All movement traces are color coded by the desired directionality of movement.

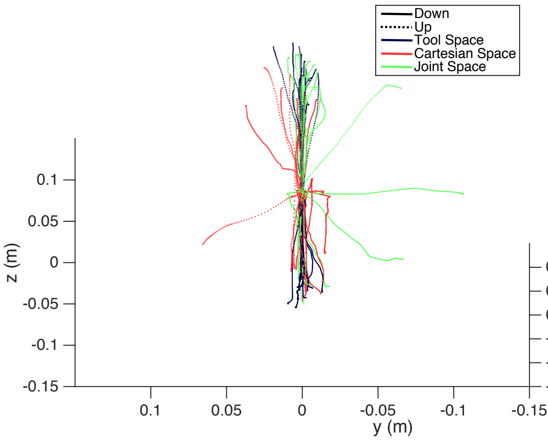
movements had less error that down and left movements respectively. The increased downward error may have been due to a flaw with the experimental setup where the desired target location was below the table surface. For left movements, as the user had to move his or her arm across the body, there could have been some bio-mechanical limitations with this movement.

Finally, user surveys of task difficulty (5-point Likert scale) were collected and statistically analyzed (Fig. 11, Table I)). Users reported that the tool space mapping was easier than the joint space mapping and that lateral movements (right/left) and rotations, were easier to interpret than the left and right diagonal movements. These results indicate that tool space is the most effective and understandable guidance mapping for simulated percutaneous needle insertion.

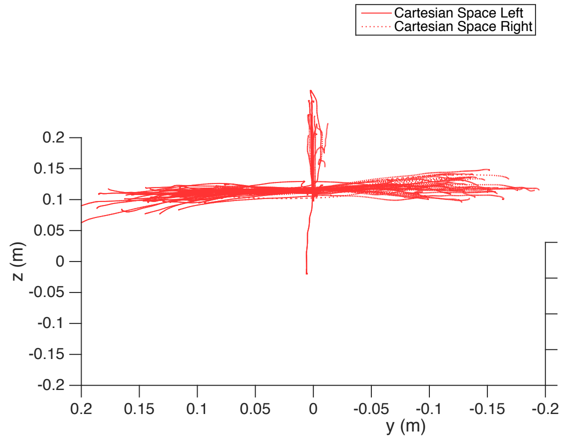
## VI. Conclusions and Future Work

In this paper, we studied the most effective and understandable vibrotacile mapping for desired needle position and orientation in a simulated 2D percutaneous needle insertion task. Our study demonstrates that a tool space mapping has the least directional error and lowest difficulty rating in a human subjects study.

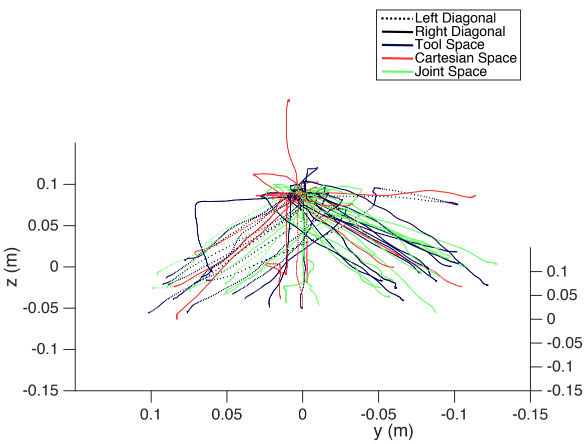
In contrast to this study, in prior work, we found the Cartesian space control was more accurate and easier to learn than tool space control for teleoperated steerable needles (note: this work using the term 'joint space' to identify needle or tool degrees of freedom) [31]. These results together pose some interesting questions regarding the roles of tool degrees of freedom and task difficultly on user preferences for control. In future work, we will expand the current study to three dimensions to identify if increase task difficulty will switch user preference as it does for steerable needles. This work is just the first step in developing a percutaneous guidance system for emergency needle insertion task. A



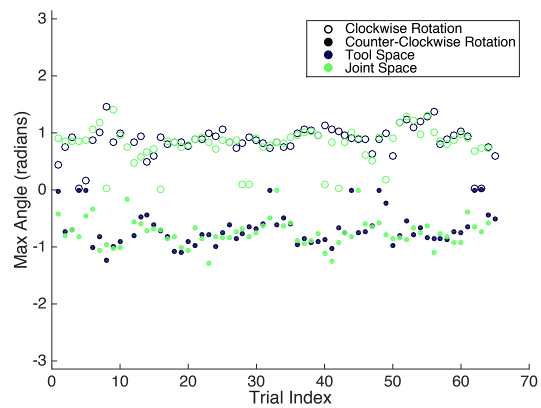

(a) Up/Down Movements, All Subjects, All Trials




(b) Left/Right Movements, All Subjects, Cartesian Space




(c) Left and Right Diagonal Movements, All Subjects, All Trials




(d) CW and CCW Rotations, All Subjects, Tool and Joint Space

Fig. 9: Specific movements from all subjects, all guidance mappings for up/down movements (a), left/right movements in Cartesian Space (b), diagonal movements in both left and right directions (c), and clockwise and counterclockwise rotations for tool and joint space mappings (d).

TABLE I: Statistical Analysis Summary

| | Guidance Mapping (TS, CS, JS) | | Direction | | Cue Type | |
|---|---|---|---|---|---|---|
| Source | $p$ | Significant Groups | $p$ | Significant Groups | $p$ | Significant Groups |
| Up/Down Directional Movement Error | $<$0.0001 | TS $<$ CS & JS | 0.0276 | Up $<$ Down | n/a | n/a |
| Diagonal Directional Movement Error | $<$0.0001 | TS & JS $<$ CS | 0.0437 | Right $<$ Left | n/a | n/a |
| User Difficulty Rating | 0.0008 | TS $<$ JS | n/a | n/a | $<$0.0001 | Lateral Mvt. & Rotation $<$ Left or Right Diagonals |

TS–tool space, CS–Cartesian space, and JS– joint space.

successful system will require a method to record user biomechanics and needle tip positions, both correlated to an estimated or known target within the patient. A more feasible intermediate step may be to allow remote experts to guide novice users by demonstrating the proper insertion with a teleoperated haptic device.

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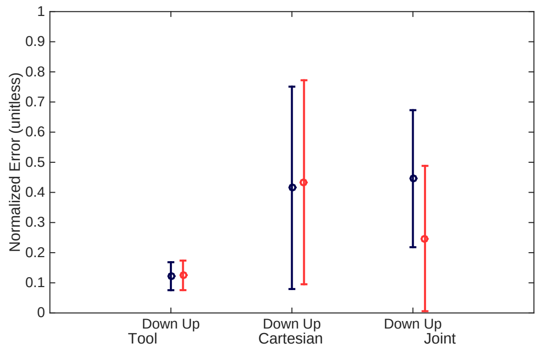
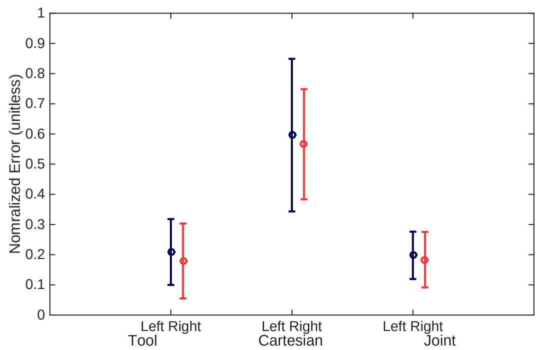



(a) Up and Down Movements




(b) Left and Right Diagonal Movements

Fig. 10: Normalized direction error for each cue and direction for down/up movements (a) or right/left diagonal movements (b). The trajectory error is obtained by first finding the unit vector between the origin and the position of the user, maximally away from the origin. The error is then computed based on the different with the known ideal needle trajectory.

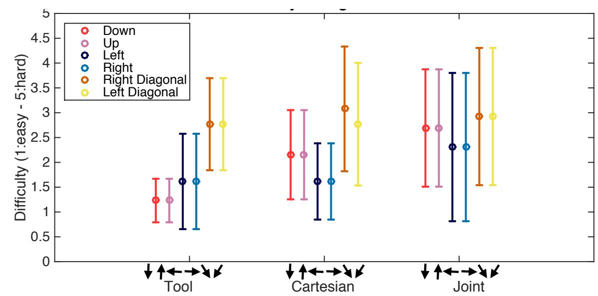



Fig. 11: Average user difficulty ratings for each mapping and movement. Users rated the difficulty of each vibrotactile mapping cue using a 5-point scale.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