

Lessons in Using Vibrotactile Feedback to Guide Fast Arm Motions

Karlin Bark*, Preeya Khanna*, Rikki Irwin*, Pulkit Kapur*, Steven A. Jax[§], Laurel J. Buxbaum[§]
and Katherine J. Kuchenbecker*

*Haptics Group, GRASP Laboratory
Mechanical Engineering and Applied Mechanics
University of Pennsylvania, USA

kbark, pkhanna, rikkm@seas.upenn.edu, pulkit.pro@gmail.com,
kuchenbe@seas.upenn.edu

[§]Cognition and Action Laboratory
Moss Rehabilitation Research Institute

jaxs, lbuxbaum@einstein.edu

ABSTRACT

We present and evaluate an arm-motion guidance system that uses magnetic tracking sensors and low cost vibrotactile actuators. The system measures the movement of the user's arm and provides vibration feedback at the wrist and elbow when they stray from the desired motion. An initial study was conducted to investigate whether adding tactile feedback to visual feedback reduces motion errors when a user is learning a new arm trajectory. Although subjects preferred it, we found that the addition of tactile feedback did not affect motion tracking performance. We also found no strong preference or performance differences between attractive and repulsive tactile feedback. Some factors that may have influenced these results include the speed and the complexity of the tested motions, the type of tactile actuators and drive signals used, and inconsistencies in joint angle estimation due to Euler angle gimbal lock. We discuss insights from this analysis and provide suggestions for future systems and studies in tactile motion guidance.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O:

1 INTRODUCTION

Computers have progressed from being isolated rooms of electronic components to devices that are increasingly intertwined with everyday human experience. Despite these advances, computers have yet to fully permeate the domain of three-dimensional space combined with naturalistic human movement. However, successful technologies such as the Nintendo Wii and Microsoft Kinect gaming controllers can be seen as a testament to the promise of this field. The next challenge in furthering the human experience in virtual reality is to provide feedback that appeals not just to vision and hearing, but to all human senses including smell, taste, and most relevantly, touch.

The field of haptics has recently given birth to a multitude of systems that seek to guide a user's movements using tactile feedback, as discussed in Section 2. These tactile motion guidance devices are worn on the body and provide corrective feedback as the user attempts to perform desired motions. Tactile feedback in motion guidance has immense potential to teach whole-body motion skills for athletics, dance, yoga, occupational training, and physical therapy. In comparison to learning motions by visually mirroring an example and receiving corrective verbal cues from an instructor, we believe tactile feedback has the potential to improve both the rate of learning and the accuracy of the learned motion. Tactile feedback may also help free the user's visual attention and provide a fun and interactive interface.

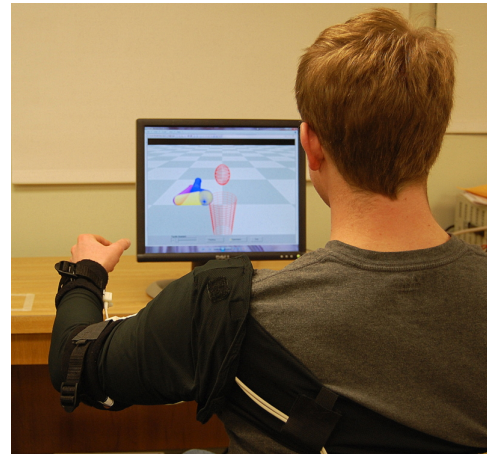


Figure 1: The tactile sleeve is worn on the user's left arm. Eight vibrotactile actuators are embedded in the sleeve (not visible), and two magnetic tracking sensors are attached via adjustable bands. The screen displays the measured arm motions (yellow and purple) and the desired (blue wire-frame) for visual feedback.

Advances in motion capture technology have opened up this field of study, but challenges remain in developing devices and algorithms for intuitive, simultaneous, multi-DoF feedback. This paper presents a system that provides vibrotactile feedback to a user as he or she attempts to replicate arm motions, as a patient would in stroke rehabilitation. After summarizing prior work in tactile motion guidance, we describe our system's components, the user study we ran to evaluate the system's effectiveness, and lessons that we hope will aid others developing tactile motion guidance devices.

2 BACKGROUND

The simplest tactile motion guidance systems detect and control one degree of freedom of human motion. For example, an array of vibrotactile actuators can be placed on a vestibulopathic patient's torso to provide balance instability alerts [1, 10, 14]. When the system detects unwanted trunk sway, it delivers vibration stimuli indicating the direction and magnitude of the error to help users regain their balance. The addition of tactile feedback was shown to reduce trunk sway significantly, demonstrating that haptics can provide valuable motion feedback to a user. However, these motions are relatively simple compared to the movements that are practiced during rehabilitation and for more advanced pursuits such as sports.

As a relatively new focus of haptics research, many of the developments in multi-DoF tactile motion guidance remain in preliminary stages. With the exception of [6, 9, 12], many have yet to demonstrate statistically significant benefits from the addition of haptic feedback, although several show promise. Here, we provide a summary of the diverse approaches being explored.

When the motions of interest involve multiple degrees of freedom, specific applications seem to need a unique tactile interface [2, 4, 5, 8, 9, 11, 12]. Actuators are strategically placed on specific joints or limbs that are identified as likely to need correction and users undergo a training session to learn how to correct their motions in response to the feedback. In [12], subjects played the violin while their bowing trajectory was monitored. Seven vibrotactile actuators were placed on their elbow, wrist, and torso to guide adjustments in posture, violin placement, and bowing hand movement. Other applications using similar methodologies include dance training [2], stroke rehabilitation [4,5], rowing [8,13], gait retraining [9], and snowboarding [11]. Advantages of this application-specific approach are that complex motions are broken down into components and that users are limited in the motion adjustments necessary; a disadvantage is that these tactile interfaces are not easily adaptable for other motor-learning applications.

Although significant research has characterized the human ability to discriminate patterns of vibration, an optimal method of applying vibrotactile sensations in motion guidance has not been determined, as evidenced by the variations in interfaces for these systems. Each developer uses different tactile algorithms, which range from providing graded vibrotactile stimuli [6], distinct levels of stimuli [14], saltatory patterns [7, 10], or some combination thereof [1, 8, 9, 11]. Recognizing this conundrum, Spelmezan et al. and Jansen et al. studied how users naturally react to vibrotactile stimuli applied on the body [3, 11]. Spelmezan et al. suggest that the spatial location of vibrations naturally conveys the body part the user should move and that saltation patterns are naturally interpreted as directional information. However, reactions to other stimuli (variations in patterns, intensity, and frequency) are not consistent. In addition, they note that some subjects react to static vibrations by moving toward the stimulus while others move away from it. Jansen et al. were able to demonstrate that users react faster to vibrotactile stimuli correlated to wrist rotation when users move toward a stimulus, and suggest that it is most intuitive to apply stimuli from an extrinsic (world) reference frame, as opposed to an intrinsic (body) reference frame. Of the above studies, [8, 9, 11–13] have tested their systems on users with promising results, but only [9, 12] have shown statistically significant results.

Finally, a select group of researchers have approached this topic from a broader point of view, developing tactile feedback systems that in theory could be used for all motion guidance activities [6, 7]. McDaniel et al. are in the preliminary stages of developing an interface that translates tactile cues to fundamental motions of the wrist and forearm [7]. A series of saltatory cues that vary in directional pattern around the arm signal the user to move their wrist and forearm joint angles. Although the authors found that subjects react to the patterns with 95.5% accuracy, the duration of each stimulus was approximately 1.3 seconds, potentially making this type of interface difficult to use with fast motions. Lieberman and Breazeal [6] were among the first to develop a fully functional tactile motion guidance system. The subject’s arm was optically tracked while they mimicked multi-DoF arm motions demonstrated by a video, and a vibrotactile sleeve provided feedback proportional to fundamental joint angle errors. The authors reported a 15% reduction in arm joint angle errors and a 7% increase in learning rate when vibrotactile feedback was combined with vision, as compared to vision alone. One drawback of this system is the optical motion capture system, which is susceptible to marker occlusion, requires a large workspace, and has a high cost (tens to hundreds of thousands of dollars), making it impractical for personal use. Nevertheless, the encouraging results from this study and others have inspired much of the work presented here.

3 TACTILE GUIDANCE SYSTEM

We are developing a practical tactile motion guidance system to provide multi-DoF feedback for universal arm motions as shown in

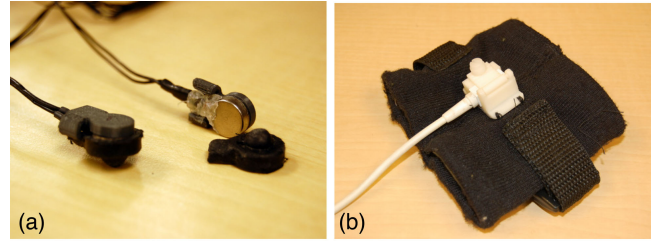


Figure 2: (a) Vibrotactile actuator caps: caps snap over fabric to attach motors to sleeve. (b) Tracking sensor mounted to a resizable cuff that is placed around the user’s arm.

Fig. 1. We call this system the StrokeSleeve because it was conceived with stroke rehabilitation in mind, though it could be used in a variety of applications. The components of our present system include a magnetic motion tracker, a vibrotactile sleeve, and a desktop PC for graphics and signal processing. The chosen components keep the system affordable for clinical use, in comparison to systems that use other motion tracking methods. Our system is updated from the design described in [4, 5] as summarized below.

3.1 Hardware

The motion of the arm is captured with an electromagnetic motion tracking system (TrakSTAR, Ascension Technology, Inc., \$4,440). Two 6-DoF sensors (19 mm × 8 mm × 8 mm) are used to detect the motion of the user’s forearm and upper arm. The system provides the position and orientation of each sensor relative to a stationary field-generating transmitter (sampling rate = 240 Hz). Measurements are accurate up to 1.4 mm (RMS) and 0.5 deg (RMS). The orientation output for each sensor is a sequence of Euler angle rotations of the sensor with respect to the transmitter reference frame. This rotational sequence is defined as an azimuth (θ_{az} about the reference frame’s Z axis), then an elevation (ϕ_{el} about the rotated frame’s new Y axis), and finally a roll (ψ_{roll} about the new X axis). Arm joint angle estimation from sensor outputs requires an initial calibration routine and subsequent calculations as outlined in Section 3.2. We estimate five joint angles of the user’s arm: shoulder abduction/adduction (γ_{Sh_ab}), shoulder flexion/extension (γ_{Sh_flex}), shoulder roll (γ_{Sh_roll}), elbow flexion/extension (γ_{El_flex}), and forearm pronation/supination (γ_{Fore_sup}).

Vibrotactile feedback is provided with eight shaftless eccentric mass motors driven by linear current amplifiers. The motors are 10 mm in diameter and are mounted to a wearable sleeve with custom, plastic, snap-fit caps. The caps (see Fig. 2a) attach the motors to the fabric of the sleeve, diminish contact area of the stimulus, and protect the motor-wire connection from breakage. The hemispherical head is sprayed with a multi-purpose rubber coating for increased friction between the cap and the skin surface.

The vibrotactile actuators interface with the user through a long, stretchable, two-layer sleeve, cut and sewn from a men’s Under Armour athletic shirt. The tracking sensors are mounted to resizable arm bands that slide over the sleeve (Fig. 2b). Four vibrotactile actuators spaced equally around the user’s wrist provide feedback of γ_{El_flex} and γ_{Sh_roll} errors. The remaining four actuators are spaced equally around the user’s upper arm, near the elbow joint, for feedback of γ_{Sh_flex} and γ_{Sh_ab} errors. Feedback of γ_{Fore_sup} error is not provided at this time. The wiring that carries current to the tactors is thin and flexible (Daburn #271 Ultra Flexible Sub-Miniature Wire) to allow the user full motion range and to minimize the transmission of vibrations beyond the point of contact. The sleeve is secured across the user’s body with an adjustable Velcro fabric strap.

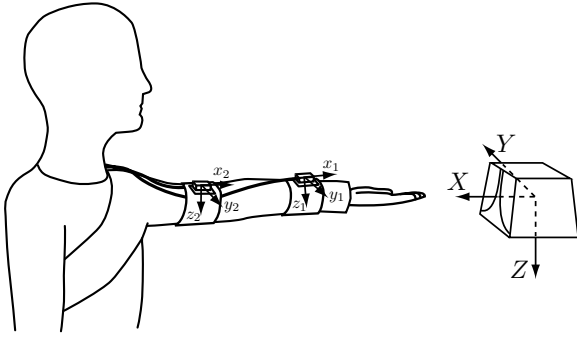


Figure 3: Pose used for calibration of motion capture system

3.2 Calibration

A calibration routine is employed to account for variations in sensor placement on the user's arm. The user is asked to stretch their arm straight out in front of them with their palm facing up, and each sensor's orientation is recorded (Fig. 3). These orientations are defined as each sensor's reference pose using a function from the TrakSTAR API. A third sensor measured torso orientation in a previous design, but we eliminated this sensor for this version to simplify the system.

Once the sensors have been calibrated, we estimate joint angles using the following equations. We define γ_{El_flex} as the angle between the x-axis of sensor 1 and the x-axis of sensor 2 with respect to the transmitter (\hat{x}_1 , and \hat{x}_2 , respectively); similarly, γ_{Fore_sup} is the angle between the y-axis of sensor 1 and the y-axis of sensor 2 (\hat{y}_1 , and \hat{y}_2 , respectively):

$$\gamma_{El_flex} = \arccos(\hat{x}_1 \cdot \hat{x}_2) \quad (1)$$

$$\gamma_{Fore_sup} = \arccos(\hat{y}_1 \cdot \hat{y}_2) \quad (2)$$

The Euler angle outputs of the second sensor (θ_{az} , ϕ_{el} , ψ_{roll}) are closely correlated with the shoulder joint movements, so we use them directly: $\gamma_{Sh_ab} = \theta_{az}$, $\gamma_{Sh_flex} = \phi_{el}$, $\gamma_{Sh_roll} = \psi_{roll}$. Because all users are required to wear the same sleeve, it is assumed that variation in limb length is minimal; therefore, limb length is not accounted for in this calibration. We use OpenGL to draw the arm on the screen as a pair of tapered cylinders with spheres at the shoulder, elbow, and hand (see Fig. 1).

3.3 Tactile Feedback Algorithm

As the user deviates from the desired trajectory, vibrotactile feedback is provided to guide them toward the correct arm pose. We chose to use a feedback algorithm that alerts the subject when joint angle errors are outside a deadband (± 10 degrees for γ_{Sh_roll} and γ_{El_flex} , and ± 15 degrees for γ_{Sh_ab} and γ_{Sh_flex}). The actuators around the wrist are responsible for indicating γ_{Sh_roll} and γ_{El_flex} errors, and the upper arm motors convey γ_{Sh_ab} and γ_{Sh_flex} errors. To describe the feedback algorithm in detail, we focus on the four actuators located around the wrist. First, the location of each motor, ϕ_j , is defined as a function of its initial orientation about the central forearm axis, $\alpha_j = (0, 90, 180, 270)^\circ$, and forearm rotation, $\gamma_{Fore_sup}(t)$:

$$\phi_j(t) = \alpha_j + \gamma_{Fore_sup}(t) \quad (3)$$

Conditional expressions are used to apply current to the motors depending on the tactile feedback mode and whether the error detected is positive or negative. The following expressions represent conditions for when angle errors ($\gamma_{err} = \gamma_{des} - \gamma_{measured}$) are negative and the subject is instructed to move their limb toward the

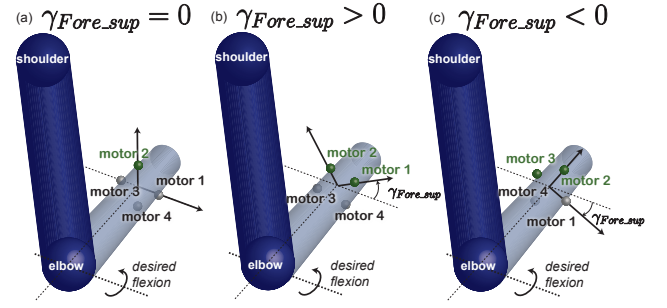


Figure 4: Illustration of motor activity to feed back γ_{El_flex} error as γ_{Fore_sup} varies (desired motion is that subject should bend elbow more). Dark green coloring indicates active motors. When (a) $\gamma_{Fore_sup} = 0$, only motor 2 is active. (b) when $\gamma_{Fore_sup} > 0$, motors 1 and 2 are active. (c) when $\gamma_{Fore_sup} < 0$, motors 2 and 3 are active.

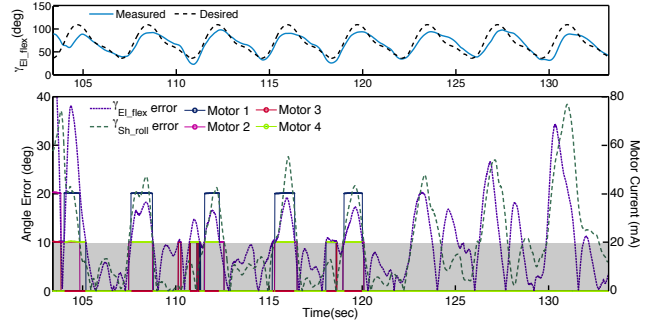


Figure 5: Wrist motor activity due to elbow flexion and shoulder roll errors. Top: Sample measured and desired γ_{El_flex} for wiping motion. Bottom: Measured $|\gamma_{El_flex}|$ and $|\gamma_{Sh_roll}|$ errors, and current sent to motors 1, 2, 3, 4 (at the wrist). No feedback is provided for the last three repetitions ($t > 120$ sec). The shaded region represents the deadband region (errors $< 10^\circ$).

stimulus to correct errors (*attraction mode*). i_{j,El_flex} is the current applied to the motor j due to γ_{El_flex} errors, i_{j,Sh_roll} is current due to γ_{Sh_roll} errors, and $i_{j,wrist}$ is the total current applied to the motors on the wrist. 20 mA of current falls within the manufacturer's specifications and was found to produce a light but noticeable 55 Hz vibration in each of the actuators. Fig. 4 illustrates the effect of γ_{Fore_sup} on motor activation for a simple case where a γ_{El_flex} error is detected.

$$i_{j,El_flex}(t) = \begin{cases} 20 \text{ mA} & \text{if } \sin \phi_j(t) > 0 \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

$$i_{j,Sh_roll}(t) = \begin{cases} 20 \text{ mA} & \text{if } \cos \phi_j(t) > 0 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

$$i_{j,wrist}(t) = i_{j,El_flex}(t) + i_{j,Sh_roll}(t) \quad (6)$$

The opposite conditions hold true for positive angle errors. Similar algorithms are used to control the actuators on the upper arm for γ_{Sh_ab} and γ_{Sh_flex} error feedback, using γ_{Sh_roll} rather than γ_{Fore_sup} . Fig. 5 shows sample data from one subject, illustrating wrist motors being activated at 20 mA and 40 mA due to the summation of γ_{El_flex} and γ_{Sh_roll} errors.

4 USER STUDY

We conducted a human subject experiment to test the efficacy of our motion guidance system for use in rehabilitation. 18 subjects (9 males, 9 females) participated in the study, ranging in age from 19 to 39 (mean = 21.8). All were right handed and performed the motions with their non-dominant arm (left arm). The subject's arm was also required to fit the sleeve, which reduced the variation in user limb lengths. Participants gave written consent prior to the study, and experiment protocols were approved by the University of Pennsylvania Office of Regulatory Affairs (IRB Protocol 809939). Each test subject was asked to move their left arm in a series of desired trajectories, chosen to match motions used in stroke rehabilitation (eating, wiping a table, cutting with a knife). These motions require complex multi-DoF coordination but are easy for subjects to understand and follow. The desired motions and corresponding body joint angles were pre-recorded by an experimenter with the tracking system and averaged across ten trials to produce smooth trajectories. We tested each subject's ability to track and learn these motions using both visual feedback (V) and visual+tactile (VT) feedback. In a rehabilitative or training environment, vision of the user's arm is always present, so a tactile (T) condition was not tested. Furthermore, it would be challenging for subjects to perform the desired motions without any visual guidance.

4.1 Setup

The vibrotactile sleeve and sensors were placed on the subject's left arm, as described in Section 3.1 and seen in Fig. 1. The subject was seated on a non-rotating stool that aligned the subject's body with the graphical representation of the torso on the computer screen. The stool also prevented inadvertent torso rotations during the experiment.

4.1.1 Calibration and Practice

The calibration routine described in Section 3.2 was completed for each subject. The subject was then allowed to move their arm for approximately 15 seconds during which they became accustomed to the virtual environment, and ensured their virtual arm matched the motion of their real arm. The calibration was repeated if the motion mapping was perceptibly distorted.

Subjects then entered a practice session where they were instructed to learn a hammering motion using both V and VT feedback. For the V feedback condition, a pre-recorded hammering motion was displayed graphically with a blue wire-frame arm, and the subject was asked to move so that their virtual arm matched the motion of the wire-frame arm (see screen in Fig. 1). The motion repeated eight times. For the first five cycles, the blue wire-frame arm was visible, but it disappeared for the remaining three. For these three cycles, the subject was instructed to repeat the motion with no feedback, though vision of their own real and virtual arm remained. In the VT practice session, vibrotactile error-correction and the blue wireframe arm were provided for the first five cycles, and they were removed for the final three cycles. In total, each subject practiced the hammering motion for two blocks of eight repetitions under each feedback condition before proceeding.

4.1.2 Experiment

The experiment phase tested three motions (eating, wiping, cutting). Both the V and VT feedback conditions were presented twice for each subject, for a total of four feedback sessions. To minimize feedback presentation order bias, half the subjects had a feedback session order of (V, VT, VT, V), and the remaining half had (VT, V, V, VT). All three motions were tested and presented in a randomized order for each feedback session to further reduce bias. As in the practice session, the subject was instructed to repeat each motion eight times, where they received feedback (V or VT) for the first five cycles and received no feedback for the last three. Prior to starting each motion, the subject was informed of the motion and

feedback mode being tested. Subjects were also able to rest at any point.

Spelmezan et. al suggest that it is unclear whether users prefer to use vibrotactile feedback in an *attraction* mode, where users react to vibrotactile stimuli by moving their limbs **toward** the stimulus, or in a *repulsion* mode, where a user moves their limbs **away** from the stimulus [11]. Because there is some evidence that users react faster to vibrotactile feedback in an *attractive* mode [3], half of the subjects in our study were tested in the *attraction* tactile feedback mode, and the other half were tested in the *repulsion* mode.

After finishing the experiment, each subject completed a written survey to record their ratings of the feedback and their general comments on the experiment. Subjects used a seven-point Likert scale to answer questions that were designed to evaluate their comfort, opinion of feedback quality, perceived effectiveness of the feedback, and overall preferences. Subjects could also provide detailed comments in open-ended sections of the survey.

4.2 Data Analysis

The main variables of interest in this study were the joint angle errors. Each joint angle error was determined by comparing the estimated joint angle to the joint angle of the desired motion. We observed that subjects often sped up their motions during the last three cycles where no feedback was provided. Thus, joint angle errors were estimated independent of motion duration for all cycles. The subject's recorded trajectory for each trial was resampled at a rate matching the recorded motion, and the joint angle error for each sample was then calculated. Errors for the first two cycles were discarded because subjects were not given time to position their arm in the correct starting pose at the beginning of a new motion, which resulted in higher errors in the first two cycles (see Fig. 5). The RMS joint angle error was then calculated for each motion in each feedback condition.

Differences between subject performance using V and VT feedback, as well as differences between the two tactile modes (*attraction*, *repulsion*), were used to determine whether either condition resulted in improved performance. We also compared subject errors during cycles 3, 4, 5 (when feedback was provided) with cycles 6, 7, 8 (when all feedback was removed) to measure the subject's ability to repeat a motion after guidance is removed.

4.3 Results

Results were analyzed and compared using repeated measures analysis of variance (ANOVA). This study is a mixed factorial experiment with three within-subjects factors (motion, joint angle, feedback condition) and one between-subjects factor (*attraction* or *repulsion* tactile feedback).

4.3.1 Joint Angle Error

In contrast to the findings of Lieberman and Breazeal [6], the addition of tactile feedback had no significant effect on joint angle error in our study. A bar graph of the average joint angle errors for all subjects can be seen in Fig. 6. For all three motions, and for all individual joint angles, there was no statistically significant difference in RMS errors between V and VT feedback. In addition, there was no statistically significant difference in RMS errors between cycles 3, 4, 5, and 6, 7, 8, indicating that users did not perform significantly better or worse when feedback was removed. When comparing the RMS errors of subjects who received *attractive* tactile feedback and those who received *repulsive* tactile feedback, there was similarly no significant difference between the two groups (see Fig. 6).

4.3.2 Survey Responses

Survey responses were rated on a 1-7 Likert scale from "strongly disagree" to "strongly agree" unless otherwise noted. We report the average and standard deviation of all subjects' responses. In general, subjects felt comfortable in the system setup (5.8 ± 1.3) and

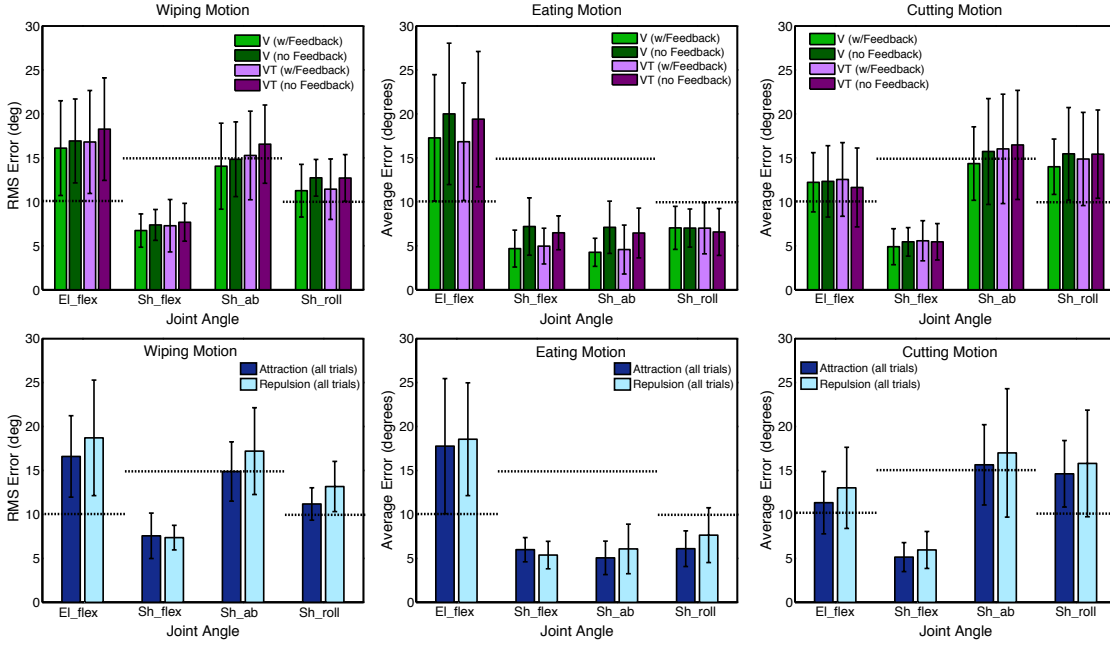


Figure 6: Overall results of user study displaying RMS joint angle errors for all subjects and for all three motions (wiping, eating, cutting). The top row organizes the RMS joint angle errors for each joint according to motion, feedback condition, and trial number. No statistically significant differences in errors were observed. The bottom row organizes errors according to motion and tactile feedback mode (*attraction*, *repulsion*) for all VT trials. There is no statistically significant difference between the two modes. Dashed lines show the deadband for each joint angle.

clearly understood the tasks and purpose of the study (6.6 ± 0.9). When evaluating the visuals in the system, most subjects provided ratings indicating that the graphic rendering of their arm represented their motions well (5.4 ± 1.4); however, in the free response section, some subjects stated that the viewing angle of the graphics and the stationary torso were distracting. On the whole, subjects felt that the blue wire frame arm displaying the desired motion trajectory was easy to follow (6.2 ± 1.1).

For the tactile feedback, subjects thought that the vibrotactile actuators were positioned correctly on their arm (6.4 ± 0.6), did not feel that the actuators varied greatly in intensity due to the position of the tactors on their arm (2.8 ± 1.4), and were neutral on whether changes to the feedback algorithm were necessary (4.2 ± 0.7). When rating the effectiveness of tactile feedback in guiding motions, subjects in general felt that the tactile feedback was guiding them toward accurate motion (5.4 ± 1.2). A few subjects commented on the difficulty of determining what direction to move in response to the feedback when multiple actuators were activated. Other subjects suggested trying the feedback mode to which they were not assigned (*attraction* or *repulsion*). Finally, 14 of the 18 subjects preferred VT compared to V feedback, with an average response of 5.5 ± 1.5 , where 1 indicated a strong preference for V feedback and 7 a strong preference for VT feedback. Of those who preferred VT feedback, a large number of subjects (10) discussed how the tactile feedback allowed them to push toward perfection or notice errors that were undetectable by vision alone. Although quantitative performance benefits were not noted, subject survey responses demonstrate that users qualitatively preferred the tactile feedback and perceived the information to be useful.

5 DISCUSSION

The quantitative results of this study were initially surprising given the previous work of Lieberman and Breazeal. However, several components of our system and approach differ from [6], and we discuss possible causes for our contrasting findings. These com-

parisons have led us to provide suggestions on how tactile motion guidance may best be used and tested in future research.

5.1 Experiment Design

Although the premise of our user study was similar to [6], the exact speed and complexity of the motions tested in [6] are unknown. Differences in motions tested between our study and [6] may have contributed to our contrasting results, although we can only report on observations from our own study. In our study, the duration of each motion ranged from 3.7 to 4.7 seconds with joint angular velocities reaching up to 90 deg/s. As a result, subjects may have had difficulty reacting to the stimuli fast enough to modify their motions appropriately. By the time a subject reacted to the stimulus, the desired joint angles and corresponding feedback had likely changed, causing subjects to record high joint angle errors.

Our study was designed to mimic rehabilitation practices that teach stroke patients everyday tasks, and the motions were described to participants as “eating,” “wiping,” and “cutting.” However, some subjects suggested that naming the actions had a negative effect on performance. For example, a subject may have performed the motion with their own “eating” motion when feedback was removed. Although the subject’s non-dominant arm was used to mollify this potential issue, this effect was still apparent in some datasets. The small number of repetitions (only five) before removing feedback also hindered our ability to observe any motor learning effects.

There are a number of suggestions for future studies. Not identifying the motions as common tasks to the subject beforehand may have better allowed us to evaluate subjects’ ability to learn motions. We also believe that providing feedback to the subject regarding their velocity errors would help mitigate confusion arising from actuator latency and delays in cognitive processing of the angle error feedback. Other work has already shown that velocity feedback can be beneficial in single DoF motion guidance [14]. Finally, the number of repetitions and speed of the motions should be selected

carefully to better allow users to both adapt to the feedback and learn new motions.

5.2 Tactile Feedback

Another aspect of our system that differed significantly from [6] was our choice of tactile actuators. [6] used high bandwidth, Tactaid voice coil actuators that allow for independent control of vibration frequency and amplitude, a property the shaftless eccentric mass motors used in our system do not allow for. The fast response times and uniform dynamics of the Tactaid actuators may result in improved subject reaction time and better localizability of the stimulus. However, the high cost of each actuator (\$80 each compared to \$3 for the motors used here) make them less desirable for practical use. Furthermore, they are no longer commercially available.

In addition, the provided vibrotactile feedback was set to a standard level rather than being proportional to the angle errors. This choice reduced the resolution of tactile feedback. Users may have benefited from receiving graded vibration magnitudes, particularly when errors were small, so that overshooting error corrections would be less likely.

Lastly, the deadbands implemented in the tactile feedback algorithms were static. An adaptive algorithm that reduces the deadband when motion tracking performance is high could have helped users achieve even smaller joint angle errors. This adaptation may have been especially helpful with the eating motion, where shoulder movements were minimal and RMS errors were small.

In the future, we plan to implement and compare using different tactile feedback algorithms to make the interface easier to understand and to challenge users to achieve smaller errors as they improve. We also plan to look beyond using vibratory cues.

5.3 Body Joint Angle Estimation

Estimating joint angles from Euler angle outputs is also unsuitable for certain motions. When $\phi_{el} = \pm 90$ degrees, Euler angles are prone to issues with gimbal lock, where θ_{az} and ψ_{roll} vary significantly due to singularities and the angles no longer correlate to body joint angles (though the overall representation of the orientation remains accurate). An alternative method of measuring and characterizing motions is recommended. In future studies, we plan to use an axis-angle representation of joint orientation error to instruct the user to move their arm in a general direction rather than determining body joint angle error measurements. When we consider how instructors guide students/patients, the instructor is more likely to touch the user and gently push the arm toward the desired location as opposed to adjusting the joint angles directly. Improving the calibration routine to incorporate limb length may also further reduce errors in motion characterization.

Another issue with our system's joint angle calculation is the location of the upper arm sensor. When subjects with larger arms attempted the eating motion and flexed their elbow, it was possible for the sensor to impede further flexion. Additionally, because the sensor is not rigidly attached to the user's arm, the sensor itself could change orientation as the muscle flexed, increasing the error of the estimated flexion angle. This may explain why the γ_{El_flex} errors were consistently higher than the other joint angle errors (Fig. 6). In order to maintain the advantages of the electromagnetic tracking system, we plan to move sensor 2 to the outside of the arm for subsequent studies. Furthermore, the Microsoft Kinect also provides an appealing low cost solution for sensing human motion, and we are currently exploring the feasibility of integrating the Kinect into our system.

6 CONCLUSIONS

Developing a practical tactile motion guidance system for multi-DoF feedback is a challenging task. This paper presents the lessons we have learned from conducting our research to assist the growing number of colleagues working on this topic. We compared a

subject's ability to follow several guided motions under visual and visual+tactile feedback using commercially available components, and we found that some of the compromises made for hardware cost and experiment design may have reduced any benefit a user would receive with tactile feedback.

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