Toward Improved Surgical Training: Delivering Smoothness Feedback using Haptic Cues

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***Abstract*—Surgery is a challenging domain for motor skill acquisition, and compounding this difficulty is the often delayed and qualitative nature of feedback that is provided to trainees. In this paper, we explore the effectiveness of providing real-time feedback of movement smoothness, a characteristic associated with skilled and coordinated movement, via a vibrotactile cue. Subjects performed a mirror-tracing task that requires coordination and dexterity similar in nature to that required in endovascular surgery. Movement smoothness, measured by spectral arc length, a frequency-domain measure of movement smoothness, was encoded in a vibrotactile cue. Performance of the mirror tracing task with smoothness-based feedback was compared to position-based feedback (where the subject was alerted when they moved outside the path boundary) and to a no-feedback control condition. Although results of this pilot study failed to indicate a statistically significant effect of smoothness-based feedback on performance, subjects receiving smoothness-based feedback altered their task completion strategies to improve speed *and* accuracy, while those receiving position-based feedback or no feedback only improved in terms of increased accuracy. In tasks such as surgery where both speed and accuracy are vital to positive patient outcomes, the provision of smoothness-based feedback to the surgeon has the potential to positively influence performance.**

I. Introduction

When we train people to do complex motor tasks, what feedback should be provided to them, and how does that feedback influence the trainee's task completion strategy? Outcome-based performance measures are limited in that they only indicate success versus failure, and do not necessarily instruct the trainee on how they should alter their strategy to achieve the desired result. Take for instance a player shooting a free throw in basketball, a task with a well-defined "success" vs. "failure" outcome metric. A player can shoot repeatedly and easily determine for each shot whether or not it was successful, but it may be very difficult for her, and even her coach, to determine why different shots resulted in success or failure. Tracking the ball's trajectory and the player's motion information, if the relevant metrics can be linked successfully with task outcomes, offers an opportunity to provide more detailed feedback that may accelerate the learning process.

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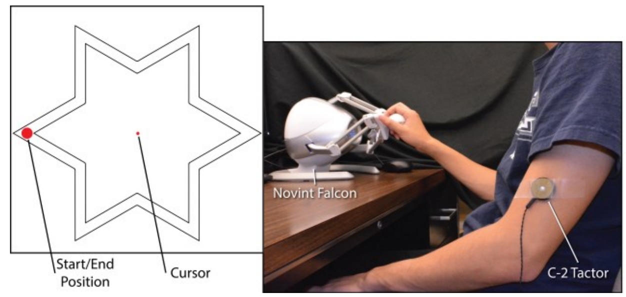

Figure 1. The subject navigates the cursor around the star shape using a Novint Falcon as the input device. In the mirror-tracing task, the movements of the input device are inverted compared to the movements of the cursor on the screen. Tactile feedback of performance is provided by a C-2 tactor secured to the subject's non-dominant arm.

This motion-based approach to performance assessment in manual control tasks is gaining traction in the research community, especially in the domain of robotic surgery. For example, some groups have measured hand and instrument movements to assess the skill level of novice and expert surgeons operating the da Vinci robotic surgical device [1,2,3]. Access to higher quantities of more detailed data about the human's control over the task and the task outcomes provides the possibility to identify performance metrics that offer multiple advantages over outcome-based metrics: insight into task performance, the ability to compare the performance of trainees in a detailed manner, and a mechanism to objectively track changes in performance as a result of training (i.e., learning curves).

Our ultimate goal is to improve surgical task performance and the efficiency of training through the provision of performance feedback that captures a user's movement smoothness. As a first step, we have identified and validated a proxy task, mirror tracing (Fig. 1) that requires the same types of movement strategies identified as successful in endovascular surgery [4]. We have demonstrated correlations between movement smoothness and performance in this mirror tracing task that we had previously observed for endovascular surgical tasks [5]. This proxy task offers a foundational experimental paradigm upon which we can design motion-based tactile feedback and evaluate the effect on manual task performance.

Coaching time for surgical trainees is expensive and extremely limited. Additionally, surgical assessment is often given informally through subjective feedback after the entire procedure is completed [6]. This delay can decouple the feedback and performance in ways that make it difficult to learn [7]. These difficulties can be assuaged in the following manner: first, the development of objective skill measurements, and second, the implementation of a near real-time feedback mechanism based on these measurements.

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Towards addressing the first challenge, we have focused on movement smoothness as an objective measure of manual skill. Movement smoothness is widely regarded as a hallmark of skilled, coordinated movement [8], and metrics that capture movement smoothness have been used to assess motor performance in basic motor control tasks [9,10], rehabilitation applications [11,12,13], and robotic laparoscopic surgery [2]. In our more recent work [5], we demonstrated the applicability of motion-based measures of performance to procedures in endovascular surgery. Analysis of movement smoothness in the frequency domain is also informative. The inherent association of "jerkiness" in a movement with higher frequencies implies the usefulness of Fourier spectrum to analyze movement smoothness [14].

This paper presents our approach to address the second challenge, wherein these smoothness-based metrics are encoded as vibrotactile cues that are displayed to the trainee during task performance. We choose a haptic modality for feedback because the application domain of endovascular surgery necessitates that feedback be practical in a surgical setting such as an operating room. These environments are inherently noisy, prohibiting auditory feedback to the surgeon. Further, endovascular surgery is extremely demanding of the visual channel, since the surgeon must observe two-dimensional live x-ray images and interpret the three-dimensional anatomy and trajectories of the endovascular tools in real-time. Within the haptic modality, our choice of vibrotactile feedback over kinesthetic feedback is intentional. Kinesthetic feedback requires complex, custom haptic devices unique to a particular task (for example, multi degree-of-freedom devices to simulate rowing [15,16] or tennis swings [17]). Further, some types of kinesthetic haptic assistance, while beneficial for enhancing performance, have been ineffective when it comes to demonstrating retention of skill or transfer to a similar task [18,19]. Tactile feedback has the potential to be widely applied for the training of complex movements in later stages when task execution strategies need to be refined, as is the case for our domain of endovascular surgery; participants are already familiar with the basics of navigating flexible catheters and guidewires to anatomical locations, but lack the dexterity to do so efficiently and repeatedly. Haptic directional cueing has already been demonstrated as an effective technique for movement guidance [20,21]. It has been shown that learning of an abstract oar trajectory on a rowing simulator was slightly more enhanced by visuo-vibrotactile feedback than by visual or vibrotactile feedback alone [22]. Studies on drawing different shapes [23] and on handwriting [24] have demonstrated an improvement in movement fluidity by the addition of haptic feedback during training, a strong parallel to our desire to train smooth tool manipulation in a surgical navigation task. To date, however, the utility of using vibrotactile feedback to convey performance feedback other than positional or trajectory error or state has not been explored. For complex tasks, feedback should be prescriptive (informing the learner on how to correct the error) rather than descriptive (simply informing about the occurrence of an error) [25]. Therefore, in this work, we evaluate the effectiveness of conveying low-level motion information to the user through vibrotactile feedback that is based on their movement smoothness, computed during task execution.

Motion-based feedback has the potential to enhance performance and training, but as the literature on training has shown repeatedly (e.g., [26]), the details of how this is done matter a great deal. Therefore, it is important to investigate exactly how to use motion-based metrics to provide feedback; what form should that feedback take, and when should it be delivered? The research presented in this paper represents the initial exploration of these questions.

II. METHODS

A. Subjects

Fifty Rice University undergraduate subjects, 17 male and 33 female, age range 17 to 23 years, provided informed consent according to the approved protocol and participated in the study. Subjects were recruited from the Psychology subject pool and received credit toward a course requirement for participation.

B. Design

This is a mixed design experiment with one between-subjects factor and two within-subjects factors. The within-subjects factors included block (5) and trials within blocks (10). The between-subjects factor, condition, was comprised of three levels: no feedback (control), position-based feedback, and smoothness-based feedback. Subject distribution was as follows: 16 in the no feedback condition, 17 in the position-based feedback condition, and 17 in the smoothness-based feedback condition. Details for the two feedback conditions are outlined in Tables I and II.

Both the position and smoothness feedback conditions used a C-2 tactor (Engineering Acoustics, Inc.) secured to the subject's non-dominant arm to deliver tactile feedback related to task performance. Position-based feedback delivered high frequency, high amplitude pulses whenever the cursor position was outside of the star shaped boundary displayed in Fig. 1.

TABLE I. POSITION-BASED FEEDBACK CUE SPECIFICATIONS, DELIVERED WHEN THE CURSOR IS OUTSIDE THE BOUNDARY

Number of Pulses	continuous
Pulse Separation (ms)	50
Pulse Duration (ms)	50
Pulse Amplitude (*)	250
Pulse Frequency (Hz)	265

* Amplitude is given as a scalar ranging from 0 to 250

TABLE II. SMOOTHNESS-BASED FEEDBACK CUE SPECIFICATIONS

	Good Performance	Average Performance	Poor Performance
SAL values	SAL < 4	4 < SAL < 5	SAL > 5
Number of Pulses	1	2	3
Pulse Separation (ms)	-	50	50
Pulse Duration (ms)	200	100	50
Pulse Amplitude (*)	125	150	250
Pulse Frequency (Hz)	200	230	265

* Amplitude is given as a scalar ranging from 0 to 250

Smoothness-based feedback consisted of three possible cues presented to the subject based on their performance (in terms of movement smoothness), determined by computing the Spectral Arc Length (SAL) [14] from the cursor data for the preceding five seconds of the task. These cues were designed to match performance with the corresponding degree of pleasantness. We chose the highest amplitude, which is perceptually the most unpleasant, to inform participants of their poor performance and encourage them to perform better. Furthermore, the peak-to-peak displacement of the C-2 tactor is highest at it resonant frequency of 265 Hz, which in turn makes it the most perceptible.

The cue for poor performance consisted of a series of three high frequency, high amplitude, and low duration pulses. The cue for average performance consisted of a series of two medium frequency, medium amplitude, and medium duration pulses. The cue for good performance consisted of a single low frequency, low amplitude, and long duration pulse. The ranges of SAL values for these three performance categories were determined from performance data gathered from 28 subjects in a continuation of the work in [4]. This three cue approach was developed through pilot testing to provide a clear and distinct indication of the user's performance based on previous research.

C. Performance Measures

Mirror tracing task performance for a given trial was evaluated based on an adjusted completion time metric (t_A). This metric incorporates components of accuracy and speed, both of which are important in endovascular surgery. It is desirable to have less contact with the vessel wall to avoid damage, therefore surgeons must navigate with good accuracy. Further, reducing overall procedure time is known to reduce medical costs, radiation exposure, and stress on the body from anesthesia and contrast agents. The t_A metric is a weighted sum of time inside (t_I, the time spent inside the boundaries during the trace) and time outside (t_O, the time spent outside the boundaries during the trace) as shown in the following equation.

$$t_A = t_I + 5t_O \qquad (1)$$

The weighting value for t_O was increased from an original value of 3 in the pilot study [4]. The data from that study revealed a high willingness of subjects to prioritize speed with relative disregard for accuracy. Thus, by increasing the penalty for time spent outside the boundary, better performance scores (t_A values) will be associated with those subjects who achieved a desirable balance between speed and accuracy.

D. Task

Subjects performed a computer version of the classic mirror tracing task pioneered by Snoddy [27]. In the original task, subjects used a metal stylus to trace around the interior of a physical six-pointed star made of brass, but subjects could not directly see either their hands or the star. Instead, they looked through a mirror, which reversed the left-right directional relationships between what subjects saw and how they actually moved, i.e., moving the stylus physically left appeared to move the stylus to the right.

Our version did not use a mirror, but rather presented the star on a computer display, as shown in Fig. 1. The task was like the original, but rather than a stylus, subjects navigated around the star using a Novint Falcon joystick, and were instructed to keep the cursor within the inner and outer boundaries. We achieved the mirror effect by reversing the controller, but this time on both axes, so an upward movement of the controller moved the cursor down. Left and right directions were similarly reversed. Inverting both axes, as opposed to a single axis as in Snoddy, had the desired effect of increasing task difficulty so that we could observe the effects of performance feedback.

E. Procedure

Each subject received instructions describing the task and the feedback (depending on condition) at the beginning of the experiment. Subjects in the smoothness-based feedback condition were allowed to experience the haptic cues associated with poor, average, and good performance. All subjects were allowed one practice trace to familiarize themselves with the task, controls, and feedback that they would receive (if relevant). Each subject then performed 5 blocks of 10 trials each of the mirror tracing task. After each block of 10 trials, subjects were encouraged to take a short break before proceeding to the next block of trials. As an incentive for performance, top performing subjects were awarded a gift card valued at $20 upon the conclusion of the study.

For each trial, the cursor started in the circle at the left-hand vertex of the star, as depicted in Fig. 1. The circle changed color from red to yellow to green, with green indicating that the subject should start moving clockwise around the star. When subjects moved outside the boundary of the star the cursor changed color from green to red and all time spent outside the star incurred penalty time according to (1). For example, if they spent three seconds outside the star, the adjusted completion time would increase by 15 seconds.

F. Materials

A Dell OptiPlex 760 running Windows 7 and Unity 5.5.2f1 was used to present the experiment on a Dell P2217 LCD monitor (55.87 cm or 22" diagonal) set to display at a resolution of 1680 by 1050 pixels. A C-2 tactor and an Engineering Acoustics tactor control unit were used to deliver feedback.

Instead of a traditional mouse or joystick, subjects provided input via a Novint Falcon three-dimensional controller. The Falcon was configured to allow input in two dimensions with a physical workspace of 7 cm x 7 cm correlating to a virtual workspace of 1000 pixels x 1000 pixels. The width of the star trace path (Fig. 1) was 42 pixels (approximately 1.2 cm on the display). Force feedback of approximately 9 N, implemented using a high stiffness virtual spring, was used to restrict movement in the third dimension.

III. RESULTS

We collected a total of 2500 trials of data (50 subjects, 50 trials each). The data for two subjects were discarded due to a high number of invalid trials; more than 25% of the trials were ruled invalid due to equipment errors in data collection. Data analysis was carried out for the remaining 16 subjects in each between-subjects condition.

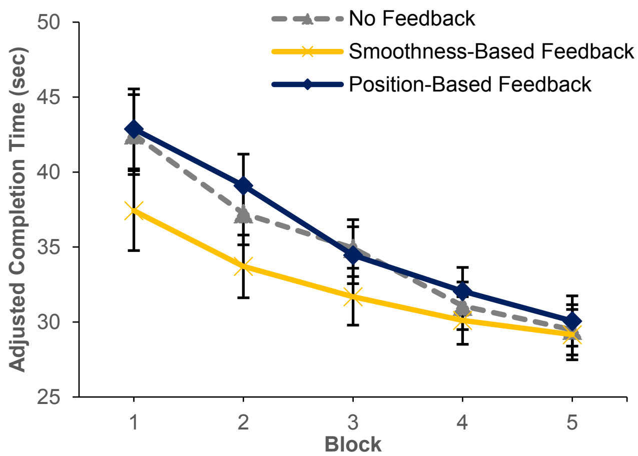

Figure 2. Overall task performance as measured by adjusted completion time (t_A) versus block, for each feedback condition. Error bars represent ± 1standard error of the mean.

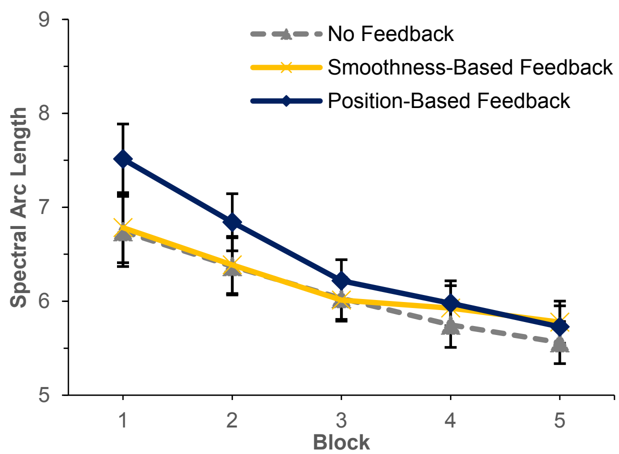

Figure 3. Spectral Arc Length (SAL, a measure of movement smoothness) versus block, for each feedback condition. Error bars represent ± 1standard error of the mean.

The adjusted completion time for each trial, shown in Fig. 2, was analyzed with a 3 (condition) x 5 (block) x 10 (trial within block) mixed design ANOVA, which showed only a significant main effect of block $F(4, 180) = 89.93$, $MSE = 172.54$, $p < .001$ (Huynh-Feldt adjusted), Cohen's $f = 1.41$. The main effect of condition was not significant $F(2, 45) = 0.86$, $MSE = 2822.09$, p = .43, Cohen's $f = 0.20$. The block and condition interaction was also not significant $F(8, 180) = 2.11$, $MSE = 172.54$, p = .068 (Huynh-Feldt adjusted), Cohen's $f = 0.31$.

The movement smoothness metric SAL was also computed for each trial (see Fig. 3). This metric was analyzed with the same 3 x 5 x 10 mixed design ANOVA, and showed only a significant main effect of block $F(4, 180) = 62.07$, $MSE = 3.32$, $p < .001$ (Huynh-Feldt adjusted), Cohen's $f = 1.17$. The main effect of condition was not significant $F(2, 45) = 0.55$, $MSE = 53.43$, $p = .58$, Cohen's $f = 0.16$. The block and condition interaction was also not significant $F(8, 180) = 2.14$, $MSE = 3.32$, $p = .061$ (Huynh-Feldt adjusted), Cohen's $f = 0.31$.

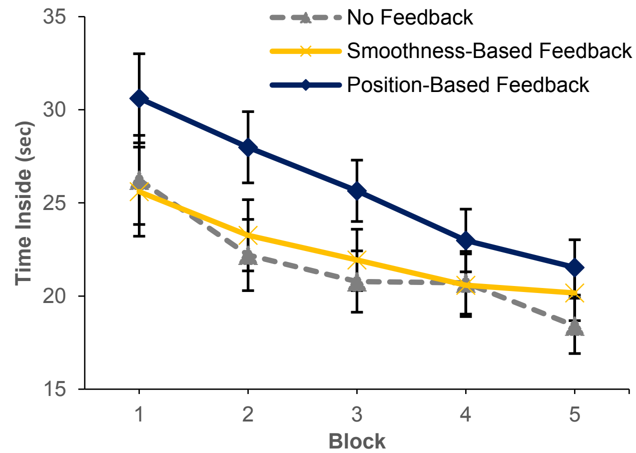

Figure 4. Time inside (t_I) versus block, for each feedback condition. Error bars represent ± 1standard error of the mean.

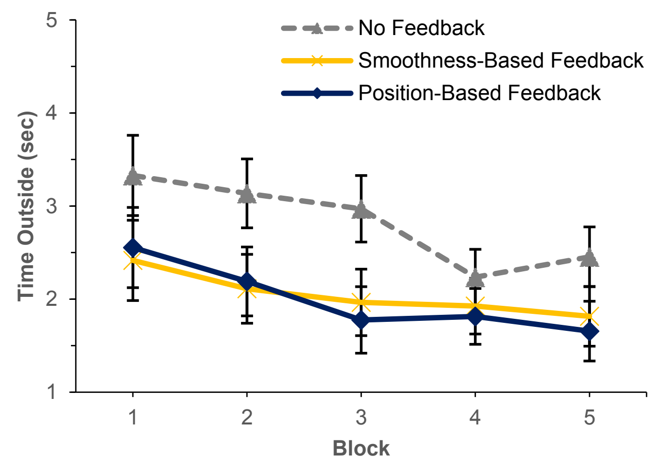

Figure 5. Time outside (t_O) versus block, for each feedback condition. Error bars represent ± 1standard error of the mean.

The time spent inside the star trace for each trial (see Fig. 4) was analyzed with the same mixed design ANOVA used showed only a significant main effect of block $F(4, 180) = 40.32$, $MSE = 177.44$, $p < .001$ (Huynh-Feldt adjusted), Cohen's $f = 0.95$. The main effect of condition was not significant $F(2, 45) = 1.65$, $MSE = 2343.54$, $p = .20$, Cohen's $f = 0.27$. The block and condition interaction was also not significant $F(8, 180) = 1.43$, $MSE = 177.44$, $p = .23$ (Huynh-Feldt adjusted), Cohen's $f = 0.25$.

The time spent outside the star trace for each trial (see Fig. 5) was analyzed with the same 3 x 5 x 10 mixed design ANOVA, and showed only a significant main effect of block $F(4, 180) = 19.65$, $MSE = 4.12$, $p < .001$ (Huynh-Feldt adjusted), Cohen's $f = 0.66$. The main effect of condition was not significant $F(2, 45) = 1.88$, $MSE = 91.93$, $p = .17$, Cohen's $f = 0.29$. The block and condition interaction was also not significant $F(8, 180) = 1.86$, $MSE = 4.12$, $p = .10$ (Huynh-Feldt adjusted), Cohen's $f = 0.29$.

These ANOVAs show the subjects demonstrated learning across the 5 blocks and all variables much like in our prior study [4]. However, none of the ANOVAs were significant for the effect of feedback condition or the interaction of block and feedback condition. The effect sizes observed for the feedback condition and the interaction of block and feedback condition ranged from the smaller side of medium to just larger than medium.

IV. Discussion

While the results were not conclusive, they were highly suggestive. In particular, it appeared that position-based feedback did little to improve overall performance, but more than that, it encouraged a strategy shift in terms of speed-accuracy tradeoff. That is, subjects who received position-based feedback did indeed spend less time overall outside the desired path than those in the control condition, but they did so at the cost of overall speed. Simply put, the data suggest that they slowed down to avoid penalty time. Reducing penalty time is desirable so this is a positive result, but slowing down is not. In the context of endovascular surgery, time is a factor. Increased time on the surgical table exposes patients to increased radiation levels.

Smoothness-based feedback, on the other hand, produced a reduction in penalty time without a concomitant overall slowdown. That is, subjects maintained good speed throughout the task without sacrificing accuracy. If this can be achieved with surgeons, we believe this will be a highly attractive training platform; increasing accuracy without sacrificing speed is ideal in many motor domains, particularly surgery.

Of course, our results only suggest this, though they did so despite the fact that many subjects claimed they did not fully attend to or even clearly understand the smoothness-based feedback. Thus, going forward we plan to give subjects more extensive training on understanding and interpreting the tactile feedback of performance based on movement smoothness.

Another factor here was likely task difficulty. Subjects in all conditions, even the control condition, learned rapidly. The current mirror-tracing task is perhaps not difficult enough in that many subjects saturated fairly quickly, making it harder to statistically distinguish the groups. We expect that the effects suggested in our data will be magnified by increased task difficulty. A more difficult task may include narrower bounds, but also sharper turns and curved sections, which has the added benefit of more accurately reflecting the kind of paths often followed by endovascular surgeons as they navigate the flexible guidewires and catheters through the branched anatomy of our vascular system.

Finally, our sample was too small to detect effects of the size observed. Follow-up experiments will thus not only incorporate more initial training and a more difficult version of the task, but a larger sample of subjects. Hopefully in combination this will generate more conclusive data.

V. Conclusion

We have designed and implemented a smoothness-based feedback technique that provides real-time feedback via vibrotactile cues to a training completing a mirror tracing task. Compared to vibrotactile feedback based solely on position, where subjects were alerted when they moved outside of a specified path boundary, the smoothness-based feedback resulted in improved accuracy without sacrificing speed. Although the data were unable to conclusively prove the superiority of this smoothness-based feedback technique, the results gave strong indications that our approach is suitable for the domain of endovascular surgery where speed *and* accuracy are equally valued. The results from this study provide the groundwork for continued research into the use of smoothness-based metrics for real-time performance feedback.

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