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Effects of attractive versus repulsive vibrotactile instructional cues during motion replication tasks

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Abstract — **The Mobile Instrument for Motion Instruction and Correction (MIMIC) enables an expert (i.e., physical therapist) to map his/her movements to a trainee (i.e., patient) in a hands-free fashion. MIMIC comprises an Expert Module (EM) and a Trainee Module (TM); both modules include six-degree-of-freedom inertial measurement units, microcontrollers, and batteries. The TM also includes actuators that provide the trainee with vibrotactile instructional cues. The estimated expert body motion information is transmitted wirelessly to the trainee; based on the computed difference between the motions of the expert and trainee, directional instructions are displayed to the trainee's skin via vibrotactile stimulation. This study examined anterior-posterior trunk movements using a simplified version of the MIMIC system in which only two actuators were used to provide feedback and pre-recorded target trajectories were used to represent ideal expert movements. The study was designed to investigate the effects of attractive versus repulsive vibrotactile instructional cues when the motion speed and task complexity were varied. Preliminary results (n = 12) suggest that repulsive vibrotactile instructional cues lead to the greatest correlation between expert and subject motion, the least time delay, and the least tilt error.**

I. INTRODUCTION

VIBROTACTILE biofeedback has been shown to improve sensory integration and motor coordination in healthy subjects and subjects with vestibular loss, traumatic brain injury, and stroke [1]. Frequency, amplitude, waveform, and duration of vibrotactile cues applied to the skin have been modulated to convey information [2], and the effects of display spatial resolution have been studied [3].

Technologies that augment traditional rehabilitation practices in the clinical setting or increase compliance in at-home based exercise programs can potentially provide both instructions regarding the intended movements and real-time or delayed feedback. Several studies have developed and assessed kinesthetic motion guidance systems with vibrotactile biofeedback for upper limb motion guidance that use a control signal proportional to the position error between the target and subject [4-6]. One limitation of these studies, however, is the bulky lab-based motion tracking systems required. The miniaturization of inertial measurement units (IMUs) has provided a means for real-time motion tracking in unconstrained environments [7].

There are two options for providing directional cues: attractive and repulsive. Attractive cues, for which individuals are instructed to move in the direction of the vibration, have previously been used to provide turning guidance during walking [8], driving [9], and flying [10] tasks and to provide pilots with information about the attitude of an aircraft with respect to gravity [10]. Repulsive cues, for which individuals are instructed to move in the direction opposite the vibration, were used by Wall et al. in the first vibrotactile feedback balance device based on the notion that such vibrations may provoke a similar aversional response as occurs when people bump into a wall [11]. While individuals can use either attractive or repulsive cuing to make volitional movements, it is possible that one of the two may result in superior performance or may better leverage non-volitional responses during certain tasks. It has been shown that stimulation of muscle proprioception by vibration may lead to non-volitional balance-correcting responses, generate illusions of movement, and modify reflex responses [12-14]. We recently demonstrated that random, non-meaningful vibrotactile stimulation (i.e., no instructions provided regarding how to respond to vibrotactile cues) over the internal obliques and erector spinae resulted in small tilt deviations on the order of 1.0° in the direction of the vibration stimulation [12]. Therefore, it is possible that repulsive cuing is actually acting in opposition to natural impulses, and hence vibrotactile feedback may in some circumstances work better by supporting reflexive responses rather than forcing the brain to think about opposing them.

The MIMIC can be configured for either attractive or repulsive cuing. In our first study with the device, we chose to use attractive cues in which subjects were instructed to move toward the vibration [15]. The purpose of this study is to determine whether or not healthy subjects exhibit a difference in performance as quantified by the expert-subject cross-correlation value and time delay and the average tilt error when using attractive versus repulsive vibrotactile cues.

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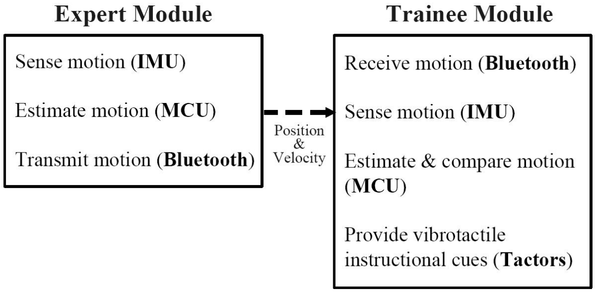

Fig. 1. MIMIC system configuration.

II. METHODS

A. System Overview

An overall representation of the MIMIC system [15] is given in Fig. 1. The device is composed of an Expert Module (EM) and Trainee Module (TM) that are used by a physical therapist and patient, respectively. Each module includes a six-degree-of-freedom inertial measurement unit (IMU), microcontroller unit (MCU), Bluetooth module, data-saving module, and battery. The TM additionally has vibrating actuators (tactors) that provide vibrotactile stimulation.

The expert's body motions are sensed by the EM IMU and processed by an extended Kalman filter (EKF) estimation algorithm. Estimated expert motions (e.g., angular displacements and velocities of the moving body segment) are transmitted wirelessly to the TM through Bluetooth communication; based on the computed difference between the expert and trainee motion, directional instructions are displayed via vibrotactile stimulation. The trainee is instructed to move toward (attractive) or away from (repulsive) the direction of the vibration until the stimulus ceases.

B. Subjects

Twelve young (24.8 ± 3.7 yrs) healthy naïve subjects (8 male, 4 female) participated in this study. The University of Michigan Institutional Review Boards approved the experimental protocol, which conformed to the Helsinki Declaration. Informed consent was obtained from each subject prior to the start of the experiment.

C. Experimental Protocol

All subjects participated in two days of testing separated by approximately 48 hrs. The subjects were divided into two groups. Group 1 (G1) subjects completed the first day of testing using attractive cues and the second day of testing using repulsive cues. The second group (G2) completed the testing in the opposite order. Subjects were instrumented with the TM and instructed to 1) stand with their feet parallel approximately 15 cm apart and 2) move either in the direction of the vibration or in the direction opposite the vibration until the vibration stops. Standard foam earplugs and earmuffs were provided to eliminate environmental and tactor noise. One tactor was placed near the navel and another near the spine at approximately the level of the L4/L5 vertebrae.

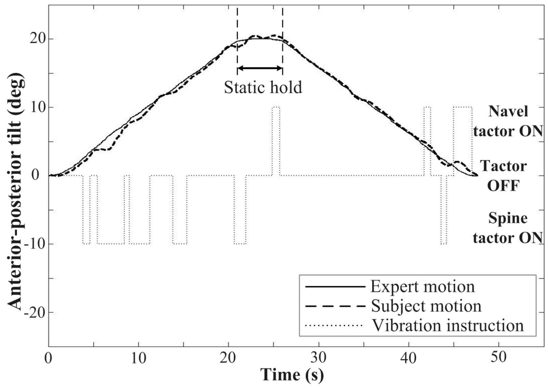

Fig. 2. Representative sample data when the slow speed was provided with repulsive cues. Solid, dashed, and dotted lines represents the expert motion, subject motion, and vibration instruction, respectively.

Subjects completed two protocols during each day of testing. During the first protocol, they were asked to replicate the recorded anterior-posterior (A/P) trunk movement, subsequently referred to as "expert motion", by moving either toward or away from vibrotactile instructional cues. Subjects were also asked to bend only at the waist in response to the instructional cues (i.e., use a hip strategy only), and were instructed to close their eyes while they performed the task. The expert motion consisted of an anterior 20° trunk bend followed by a 6 s static hold at 20° and a posterior trunk bend to return to neutral upright stance (see Fig. 2). Subjects performed the movement at three different speeds: slow (approximately 1.0°/s), medium (approximately 2.0°/s), and fast (approximately 4.0°/s). During the second protocol, subjects were asked to use the vibrotactile cues to replicate four more challenging sequences of A/P trunk bends (patterns 1-4) with variable speeds [15]. The MIMIC controller used a 0.5° error threshold and proportional plus derivative feedback control signal based on the results of a previous study [8]. Three practice trials for each speed and pattern were performed prior to the experimental session.

Figure 3 shows sample data from one subject when the subject was provided with repulsive vibrotactile instructional

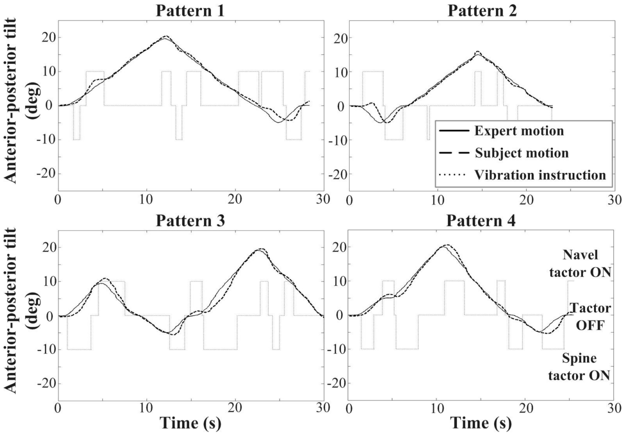

Fig. 3. Representative sample data when the patterns were provided with repulsive cues. Solid, dashed, and dotted lines represents the expert motion, subject motion, and vibration instruction, respectively. Positive values indicate movement in the anterior direction.

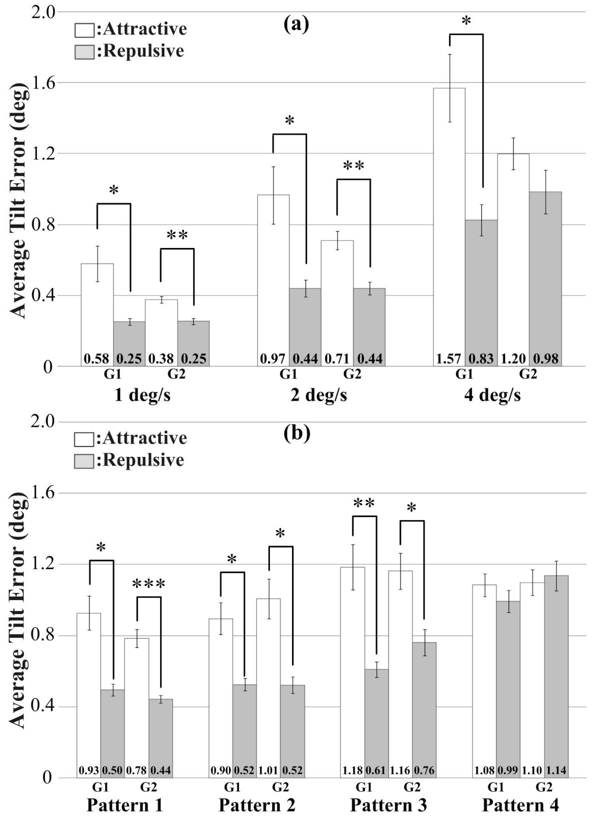

Fig. 4. Average expert-subject tilt error for each group as a function of (a) protocol 1 motion speed and (b) protocol 2 pattern. White and gray bars represent attractive and repulsive vibrotactile instructional cues, respectively. Error bars represent standard error of the mean (*$p<0.05$, **$p<0.01$, ***$p<0.001$).

cues while performing four different patterns. Subjects completed three repetitions for each speed and pattern. Presentation of trial type was randomized. Subjects were required to rest for 20 s between trials and took a mandatory 10 min break every 20 min.

D. Data Analysis Methodologies

All post-processing was performed using MATLAB (The MathWorks, Natick, MA). To characterize subjects' ability to replicate the expert motion, a cross-correlation analysis of the expert and subject trunk tilt was performed. The output of the cross-correlation analysis was 1) a cross-correlation value ranging between 0 and 1, with 1 indicating perfectly matched motion, 2) a time delay, with a positive delay indicating time lag between the expert and trainee motion, and 3) tilt error, defined as the average absolute difference between the expert and subject tilt angles in degrees.

A two-way analysis of variance was conducted to determine the main effects of cue instruction (attractive vs. repulsive) and motion condition (speed and pattern) for each dependent variable. Hypotheses for the main effects and their interactions were tested using an F-test. Post-hoc analysis for each dependent variable was performed using Tukey Honestly Significant Differences.

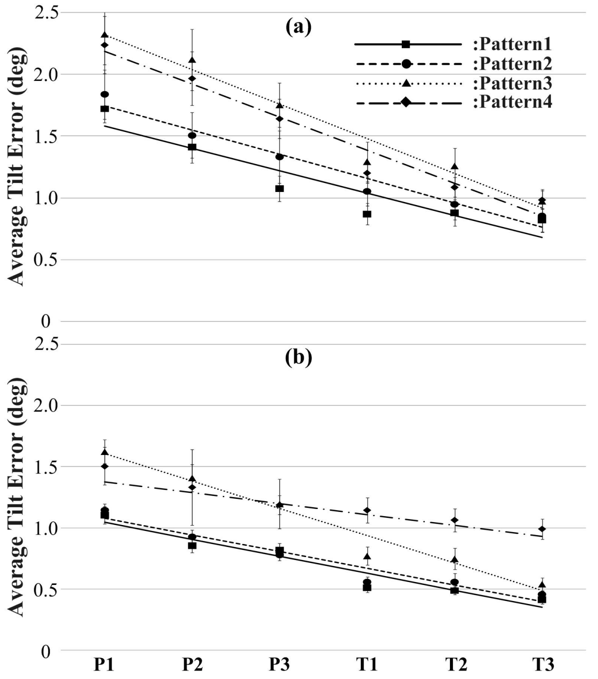

Fig. 5. Average expert-subject tilt error versus trial number for the four patterns of protocol 2 under (a) attractive and (b) repulsive cuing. P and T represent practice and experimental trials, respectively. Error bars represent standard error of the mean.

III. RESULTS

Speed: Figure 4(a) presents the average expert-subject tilt error as a function of speed during the first protocol. Analysis of the expert-subject tilt error (cue: $F(1,60)=33.90$, $p<0.001$; speed: $F(2,60)=59.09$, $p<0.001$), cross correlation (cue: $F(1,60)=6.86$, $p=0.011$; speed: $F(2,60)=8.72$, $p<0.001$), and time delay (cue: $F(1,60)=13.49$, $p=0.001$; speed: $F(2,60)=7.58$, $p=0.001$) showed significant main effects of vibrotactile instructional cue type and speed. Subjects from both groups had the smallest tilt errors and time delays and largest cross-correlation values when repulsive cues were provided. As motion speed increased, performance decreased. The smallest tilt errors and largest cross-correlation values occurred when the motion was replicated at the slowest speed. G2 subjects consistently outperformed G1 subjects during this protocol. Four of the six G1 subjects stated a preference for repulsive cuing while four of the six G2 subjects stated a preference for attractive cuing.

Pattern: Figure 4(b) presents the average expert-subject tilt error as a function of movement pattern during the second protocol. Analysis of the expert-subject tilt error (cue: $F(1,80)=47.89$, $p<0.001$; pattern: $F(3,80)=16.32$, $p<0.001$), cross correlation (cue: $F(1,80)=23.78$, $p<0.001$; pattern: $F(3,80)=4.69$, $p=0.005$), and time delay (cue: $F(1,80)=51.29$, $p<0.001$; pattern: $F(3,80)=4.27$, $p=0.008$) showed significant main effects of vibrotactile instructional cue type and pattern. Subjects consistently performed best in terms of minimizing tilt errors and time delays and maximizing cross-correlation values when repulsive cues were provided during patterns 1, 2, and 3. No differences in performance were observed when subjects performed pattern 4, which was considered to be the most difficult since it included a short static hold while the other three patterns did not. G2 subjects outperformed G1 subjects for patterns 1-3.

Figure 5 presents the average expert-subject tilt error versus trial (three practice trials followed by three experimental trials) for each of the four patterns of protocol 2 under (Fig. 5a) attractive and (Fig. 5b) repulsive cuing. Attractive cuing consistently exhibits a greater initial error as well as a greater decrease in error over the course of the trials, suggesting that a longer training/practice time is required for attractive cuing to achieve tilt error comparable to repulsive cuing.

Table 1 presents the average expert-subject tilt error for the four patterns by group, preference, and cue type. G1 subjects who preferred repulsive cuing performed significantly better using repulsive cuing for all patterns.

TABLE I
AVERAGE EXPERT-SUBJECT TILT ERROR FOR THE FOUR MOTION PATTERNS BY GROUP, PREFERENCE, AND CUE TYPE.

G	P	Cue	Pattern 1		Pattern 2		Pattern 3		Pattern 4	
1 (n=6)	A (n=2)	A	0.48		0.60		0.78		0.64	
		R	0.30		0.51		0.40		0.40	
	R (n=4)	A	0.85	*	0.86	*	0.88	*	1.01	*
		R	0.44		0.42		0.48		0.50	
2 (n=6)	A (n=4)	A	0.56	*	0.70		0.92		0.99	
		R	0.40		0.54		0.60		0.75	
	R (n=2)	A	0.67	*	0.85	*	0.70		0.84	
		R	0.18		0.33		0.49		0.34	

G=group, P = preference, A = attractive, R = repulsive, *$p<0.05$.

IV. DISCUSSION

Repulsive vibrotactile instructional cues resulted in the greatest correlation between expert and subject motion, the least amount of time delay, and the least amount of average tilt error when the motion speed and task complexity were varied. Subject preference for a particular cue type was dependent on the order of vibrotactile cues provided: G1 subjects received attractive cues first, but preferred repulsive, while G2 subjects received repulsive cues first, but preferred attractive. This may indicate that subjects were more comfortable with the experimental protocol on the second day of testing. However, subjects' tilt errors were minimized with repulsive cues even if they responded that they preferred to use attractive cues. Furthermore, subjects performed best when using repulsive cues regardless of whether they completed repulsive cuing trials on the first or second day of testing.

Analysis of learning effects suggests that additional training trials beyond those conducted here are required to reach steady-state performance and draw conclusions regarding whether one cuing strategy is better than the other during long-term use. However, for short-term applications such as a rehabilitation setting in which training time may be limited, this study suggests that repulsive cues may be preferable. Such cues may be more intuitive because they mimic the light touch of a therapist guiding the patient to a target position.

Future work includes extended training sessions to determine whether performance differences between attractive and repulsive cuing exist for long-term use.

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