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Effects of Vibrotactile Feedback on Human Learning of Arm Motions

Karlin Bark,

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104 USA

Emily Hyman,

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104 USA

Frank Tan,

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104 USA

Elizabeth Cha,

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104 USA

Steven A. Jax,

Moss Rehabilitation Research Institute, Elkins Park, PA 19027 USA

Laurel J. Buxbaum, and

Moss Rehabilitation Research Institute, Elkins Park, PA 19027 USA

Katherine J. Kuchenbecker [Member, IEEE]

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104 USA

Karlin Bark: kbark@seas.upenn.edu; Katherine J. Kuchenbecker: kuchenbe@seas.upenn.edu

Abstract

Tactile cues generated from lightweight, wearable actuators can help users learn new motions by providing immediate feedback on when and how to correct their movements. We present a vibrotactile motion guidance system that measures arm motions and provides vibration feedback when the user deviates from a desired trajectory. A study was conducted to test the effects of vibrotactile guidance on a subject's ability to learn arm motions. Twenty-six subjects learned motions of varying difficulty with both visual (V), and visual and vibrotactile (VVT) feedback over the course of four days of training. After four days of rest, subjects returned to perform the motions from memory with no feedback. We found that augmenting visual feedback with vibrotactile feedback helped subjects reduce the root mean square (rms) angle error of their limb significantly while they were learning the motions, particularly for 1DOF motions. Analysis of the retention data showed no significant difference in rms angle errors between feedback conditions.

Index Terms

Haptic interfaces; motion guidance; rehabilitation robotics; user interfaces; vibration

I. Introduction

Traditional methods of teaching motor skills often center on an instructor providing targeted feedback to adjust the trainee's movements. This feedback can come in the form of verbal cues, such as "lift your arm higher," or visual cues that range from demonstrating the proper movement to reviewing a sophisticated motion capture recording. It is also common for a coach or therapist to grasp the limb of the trainee and move it along the proper trajectory so that he or she can experience the desired motion. One potential drawback of these traditional methods is that the feedback is not provided in real time, so trainees may be unsure of precisely when and how to correct their motions. In more recent years, advances in motion detection technology have made it feasible to assess human movement instantaneously and with high accuracy, creating the possibility of teaching motor skills using new interaction methods. In particular, multi-modal interaction devices that incorporate tactile feedback to guide an individual's motions have become increasingly popular and span a wide range of application areas, including athletics [1]–[7], performing arts [8], [9], and rehabilitation [10]–[19]. The idea of using real-time tactile cues to correct motion errors is appealing because the subject can receive spatially localized feedback while performing the motion normally, without needing to shift their visual attention.

Vibrotactile feedback has been shown to be an effective means of delivering tactile cues to humans. The small size of vibrotactile actuators allows them to be embedded in lightweight garments that do not hinder the movement of the wearer [20], [21]. Actuators placed in almost any location on the skin can deliver vibrotactile cues that the wearer can detect [22], and modulating the frequency and amplitude of vibration provides variation in the stimuli that users can distinguish [15], [23], [24]. Cipriani *et al.* [23] found that when frequency and amplitude of vibrations of an actuator on the forearm varied coherently, users were able to discriminate between the different vibrotactile stimuli with higher accuracy. Stepp *et al.* [24] explored vibration as a sensory substitute for controlling manipulation forces of a prosthetic hand, and they similarly found that varying the vibration parameters enabled users to distinguish between multiple stimuli. Prewett *et al.* [22] performed a meta-analysis on 45 studies to determine the conditions under which vibrotactile feedback is most effective at improving task performance. They found that vibrotactile feedback was most effective when it provided redundant information, supplementing another modality such as vision, rather than replacing the feedback of another modality.

Although several studies have sought to determine how effectively subjects can respond to different types of vibrotactile stimuli within the realm of motion guidance, most systems have been tested using motions that are much simpler than the multi-joint movements encountered in realistic motor-skill-learning applications. Furthermore, systems that provide motion feedback using vibrotactile cues also vary in the temporal patterns of vibrations applied, the levels of stimuli used, and the spatial distribution of the vibrations. For example, both Spelmezan *et al.* [25] and McDaniel *et al.* [26] use saltation patterns of vibration to

convey motion direction. McDaniel *et al.* found that the most intuitive saltation patterns are applied in a “follow me” pattern, where the vibration direction is tangential to the movement direction. In contrast, Spelmezan *et al.* opted for a more traditional “push/pull” paradigm where vibration patterns are applied along the length of the limb [25]. Although recognition accuracy with the saltation method is high, subjects’ reaction times to saltatory patterns can range from 2.5 to 4.5 s [26], making these patterns difficult to use for real-time motion correction. Stationary vibration stimuli, where the location indicates the direction of the error, can be understood over shorter durations (200–500 ms) [12], [13], [27], [28], making them more suitable for dynamic motion guidance.

One promising application of a tactile motion guidance system is to allow rehabilitation patients to practice motions on their own and receive guidance on how to improve their movements without the constant presence of a coach or therapist. However, the use of tactile feedback in motor skill acquisition has been shown to have mixed results, and the long-term effectiveness of the feedback has been relatively unexplored. Sienko *et al.* have developed a system that delivers vibration cues around the waist to control body posture. They successfully demonstrated that users can follow the body tilt motions of a trainer using an array of vibration actuators [17] and that patients can use the system to modify their medial lateral trunk tilt to improve their postural sway [16]. Greater benefits of the feedback were seen in the more complex tasks, and patients preferred to receive the feedback continuously rather than at discrete moments; longer term retention has not yet been tested. Other relevant work from Marchal–Crespo *et al.* [6] and Sigrist *et al.* [7] has focused on using kinesthetic haptic guidance in sports applications, including how such feedback affects learning. Marchal–Crespo *et al.* [6] evaluated the effect of haptic and visual augmentation on learning a tennis forehand stroke and found that haptic guidance enhanced motor learning of the stroke as compared with using visual feedback alone. Their findings indicated that a subject’s initial skill level impacted the effectiveness of the feedback, where haptic feedback had a greater effect on novices and visual feedback benefited the more skilled participants. There was also preliminary evidence that haptic feedback may be most effective at helping someone learn the temporal aspects of a motion.

Similarly, Sigrist *et al.* [7] studied users’ ability to learn a 3-D rowing motion using visual, audio, and haptic feedback. In this work, subjects were asked to spend three days learning a rowing motion under various feedback conditions and return one week later to test their retention of the motion. In contrast to the other studies, the findings from Sigrist *et al.* indicate that terminal visual feedback was most effective for learning and retaining the motor skills involved in the task. Although subjects were able to reduce motion errors when receiving concurrent visual and haptic feedback, when the feedback was removed during the retention trials, the skills of those subjects who learned the motion under the visual and haptic feedback trials were diminished to a greater extent. One hypothesis for this finding was that the provided visual feedback was able to show users the entire motion at once, allowing subjects to preplan their movements accordingly, whereas the haptic feedback was provided only at specific moments of the motion, which prevented subjects from processing skills needed to learn the overall motion. However, Sigrist *et al.* also demonstrated that haptic feedback could be beneficial at providing timing errors and velocity ratio errors rather

than guidance on gross motion. Although haptic feedback has shown promise in some applications for motion guidance, the conditions under which the feedback is effective remains unclear [29].

The fidelity of haptic feedback varies greatly between systems and can impact how useful the feedback is to the user. Haptic motion guidance systems often use expensive motion sensing systems and/or expensive tactile actuators, e.g., [6], [7], making these systems impractical for use in everyday settings such as the home. Furthermore, a key aspect of the systems developed by Marchal–Crespo *et al.* and Sigrist *et al.* is that the tasks focused on controlling an end effector (tennis racquet, rowing oar), and the precise orientation of the user's limbs was not considered. In certain rehabilitation populations, such as left hemisphere stroke, the orientation and coordination of the joints may preclude optimal task completion [30]. Thus, there is considerable interest in the effectiveness of tactile feedback provided by lightweight, lower-cost vibrotactile actuators worn on the user's body to correct precise joint orientation, as shown by [11]–[17].

To improve the rehabilitation process, we have sought to develop a low-cost system that can supplement the training and feedback of a therapist for rehabilitation of a patient's arm after stroke. Because tests of our initial system showed that its vibrotactile feedback did not significantly affect the motion errors of healthy subjects [31], we made considerable modifications to the system's hardware and software to improve upon our previous work. This paper evaluates the effectiveness of our new system at reducing the motion errors of healthy subjects learning new arm movements. In contrast to our previous studies and other related work, the research presented here tests subject performance with and without additional vibrotactile feedback for a wider range of motion difficulties, learned over multiple days, to enable us to determine whether vibrotactile feedback provides any long-term motor learning benefits.

II. Materials and Methods

A. Motion Guidance System Overview

We have developed a low-cost vibrotactile motion guidance system that tracks the user's arm motions and provides real-time multi-degree-of-freedom (multi-DOF) visual and tactile feedback to help the user learn a desired motion trajectory (Fig. 1). Named StrokeSleeve, our system prescribes a desired motion by showing a moving wireframe representation of the arm on a computer screen. The screen also displays an avatar that moves its torso and arm in real time with the user. The user's task is to move his or her arm so that the avatar's arm stays within the wireframe arm. If the user's arm deviates from the desired trajectory, he or she immediately receives visual and vibrotactile cues to correct the motion. The main components of this system include motion tracking, visual feedback, and vibration feedback, as described in the following subsections.

1) Motion Tracking—Although our previous prototype estimated arm motions using magnetic tracking [31], our current system tracks the user's body movements with a Microsoft Kinect 360. The Kinect is a low-cost (\$100 USD) non-contact motion sensing accessory for the XBOX entertainment system; it uses an 8-bit RGB camera and an 11-bit

depth camera to detect and process motions and gestures via a proprietary algorithm developed by PrimeSense Ltd. [32]. The camera generates depth maps with a resolution of 640×480 at a rate of approximately 30 Hz, and the resolution of the sensor is 3 mm in the horizontal plane and 1 cm in depth [33]. To interface with the Kinect, we use the OpenNI open-source framework and the PrimeSense NITE middleware packages. The PrimeSense NITE algorithms return the estimated positions and orientations of the user's joints with respect to the environment. We decided to use the Kinect rather than magnetic tracking because of its lower cost, improved accuracy at tracking human movement, and insensitivity to electromagnetic interference.

For this study, we are interested in tracking only the user's torso and dominant arm. Hence, we consider the measured orientation of the following three skeleton elements: the torso (${}^N\mathbf{R}_{T,\text{meas}}$), the upper arm (${}^N\mathbf{R}_{U,\text{meas}}$), and the forearm (${}^N\mathbf{R}_{F,\text{meas}}$), where the preceding N indicates that the matrix is expressed in the environment frame. The PrimeSense NITE joint orientation outputs are such that $\hat{y}$ is aligned with the central axis of the user's torso and is $\hat{x}$ aligned with the central axis of the arm segments. Unit row vectors representing the orientation of the user's upper arm and forearm can then be expressed as follows:

$${}^N\vec{P}_{U,\text{meas}} = \hat{x} \cdot {}^N\mathbf{R}_{U,\text{meas}} \quad (1)$$

$${}^N\vec{P}_{F,\text{meas}} = \hat{x} \cdot {}^N\mathbf{R}_{F,\text{meas}} \quad (2)$$

Once the user's body pose is known, it can be compared to desired orientations to determine motion errors, as described in Section II-A3. Note that the Kinect cannot measure wrist pronation and supination, so the forearm orientation estimate it returns may not perfectly match the user's pose.

2) Vibrotactile Feedback—Our system provides the user with vibrotactile motion guidance via inexpensive components. The user wears two arm bands that are cut and modified from McDavid compression arm sleeves (\$18 each); one is placed around the bicep near the elbow joint, while the other slides over the wrist (Fig. 1). A total of eight 10-mm-diameter shaft-less eccentric mass motors (Precision Microdrives 310-101, \$10 each) are mounted to these arm bands using custom plastic snap-fit caps. Each band has four equally spaced actuators, as seen in Fig. 2. Motors located around the wrist provide feedback to correct motion of the forearm, while motors located around the bicep guide the upper arm. Different sized arm bands (S, M, L) for both arm segments are available to accommodate various users. To allow full motion range and minimize the transmission of vibrations beyond the point of contact, we use thin and flexible wiring to carry current to the vibrotactile actuators (Daburn #271 Ultra Flexible Sub-Miniature Wire).

The magnitude and frequency of vibration generated by the actuators are coupled and vary as the applied voltage increases. We measured a representative actuator's output using a high-bandwidth MEMS-based accelerometer (ADXL78) while the arm band was placed on a user's arm. As seen in Fig. 3, both the magnitude and frequency of vibrations increase

approximately linearly as the input voltage increases. The error in frequency measurements is approximately ± 10 Hz at lower voltages and ± 2 Hz at higher voltages, and the magnitude of vibrations varied depending on the location where it was placed on the arm, though the linearly increasing pattern remained consistent.

3) Tactile Feedback Algorithm—To help users benefit from the tactile feedback, we sought to develop a simple and intuitive vibrotactile interface. Although other general motion guidance systems use roll, pitch, and yaw body joint angle errors to measure the orientation of each arm segment [11], [18], [27], we found that this approach tended to confuse users, especially near representational singularities [31]. Instead, we designed a feedback algorithm that determines an error vector for each arm segment and delivers vibrotactile feedback that attempts to emulate the guidance a physical therapist might provide their patient, where motion corrections can be provided by a single, gentle, touch to move the patient's arm in a desired direction.

First, the desired orientation of each arm segment is obtained from a previously recorded trajectory. Because our system does not incorporate feedback to correct a user's torso orientation, the desired arm segment orientations are transformed with respect to the user's measured torso rotation. This step ensures that the desired trajectories each user encounters are independent of deviations in their posture and stance relative to the Kinect sensor. The desired upper arm and forearm vectors are determined as follows, where ${}^T\mathbf{R}_{U,des}$ and ${}^T\mathbf{R}_{F,des}$ are the prerecorded rotation matrices of the upper arm and forearm relative to the pre-recorded torso

$${}^N\vec{P}_{U,des} = \hat{x} \cdot {}^N\mathbf{R}_{T,meas} \cdot {}^T\mathbf{R}_{U,des} \quad (3)$$

$${}^N\vec{P}_{F,des} = \hat{x} \cdot {}^N\mathbf{R}_{T,meas} \cdot {}^T\mathbf{R}_{F,des} \quad (4)$$

The magnitude of the error for each arm segment can then be calculated as follows:

$$\theta_{error} = \arccos^{-1} \left(\frac{{}^N\vec{P}_{des} \cdot {}^N\vec{P}_{meas}}{\|{}^N\vec{P}_{des}\| \|{}^N\vec{P}_{meas}\|} \right) \quad (5)$$

For each arm segment, we then determine which single actuator will help the user minimize the error found above. We chose to activate only one actuator on an arm segment at a given time to simplify the feedback provided to the user. The vibration algorithm can be designed so that the user moves toward the stimulus or away from the stimulus. Although some research has shown that there are no performance differences associated with the two modalities [1], [31], Lee *et al.* [34] found that a repulsive feedback mode could be more effective, so we chose to employ a repulsive feedback mode to invoke the perception of the gentle push of a physical therapist.

In its most efficient form, the vibrotactile feedback should help guide the user along the plane in which both the desired and measured arm segment vectors are located; with just

four actuators available per band, we find the actuator that will most closely instruct the user to follow this plane. This is the actuator located farthest from the desired position vector.

As an example, we describe the calculations for the four actuators located around the wrist, but the same set of equations and principles are applied to the actuators on the upper arm. The position vector of each of the four motors, ${}^N\vec{P}_{m,i}$, is defined as a function of its initial position about the central forearm axis, $\theta \in (0, 90, 180, 270)^\circ$, l , a fixed distance along the length of the forearm that approximates the distance between the elbow and the motors, and r , a fixed distance that represents the radius of the arm

$${}^N\vec{P}_{m,i} = [l\hat{x} + r\cos(\theta)\hat{y} - r\sin(\theta)\hat{z}] {}^N\mathbf{R}_{F,meas}. \quad (6)$$

Once the four ${}^N\vec{P}_{m,i}$ are known, we find the distance between each motor and ${}^N\vec{P}_{F,des}$, and we choose to activate the actuator located farthest from the desired position vector. A graphical representation of the joint angle error calculation can be seen in Fig. 4.

Attempting to match an orientation with zero error is onerous; therefore our system provides vibration feedback only if the magnitude of the error is outside a specified deadband. In pilot tests, we found that a small, fixed deadband made users frustrated when learning difficult motions because they thought the vibrotactile feedback was on too frequently. To alleviate this frustration but still help users reduce their joint angle errors, our system employs an adaptive deadband scheme, where the deadband starts large (20°) when one is first learning a motion, but decreases as one's performance improves.

Inspired by psychophysical testing methods [35], we devised a three-up-three-down deadband adjustment scheme: if a user's average root mean square (rms) angle error for both the upper arm and the forearm was less than the current deadband for three consecutive repetitions, the deadband decreased by 2° . In contrast, if the average arm segment angle errors exceed 45° for three consecutive repetitions, the deadband increased by one degree. To avoid situations where vibrations were felt frequently despite small rms errors, the deadband also increased by 1° if the actuators were active for more than 50% of the time required to complete the motion. Deadbands were allowed to range from 0° to 20° . The asymmetric step size was chosen to continually push users to improve their performance. It is important to note that the deadbands for the arm segments were not independent and were limited by the segment with the larger rms angle error. This was done to keep the visual representation of the desired motion consistent, but it also resulted in the possibility of limiting how much the user could reduce the rms angle error for an individual arm segment.

Finally, to provide the user with a better sense of how large their current errors were, the vibration magnitude was scaled to reflect to the magnitude of the joint angle error outside of the deadband. To adjust for the nonlinearity of perceived magnitude of vibrations [36], [37], an exponentially increasing voltage was applied. Fig. 5 shows the voltage commands sent to the actuator; it was activated with a minimum of 1.1 V to ensure the eccentric mass began rotating, and the voltage was capped at 3.5 V to respect the rated limits of the actuator.

4) Visual Feedback—The measured and desired motions are rendered using OpenGL on a computer monitor located directly in front of the user. A representation of the user appears on-screen and is oriented such that the user's own motions and the avatar's motions are parallel (i.e., not mirrored). This view was intuitive for users to follow and minimized the amount of time where one graphical body segment overlapped with another, which would occlude portions of the movement from the user's view. The user's torso is displayed as a tapered, dotted cylinder to further minimize occluding the arm segments with other body parts, and the upper arm and forearm are displayed as a pair of solid tapered cylinders with spheres representing the shoulder and elbow. To address the Kinect's lack of wrist tracking, a simple hand is drawn at the hand pose estimated by the Kinect to allow the user to see how their wrist should be rotated. A wireframe arm displays the desired arm orientation, and the diameter of the wireframe scales appropriately with the deadband. To provide additional visual cues about the deadband, the color of the wireframe arm changes with the size of the deadband.

Fig. 6 presents a screenshot of the visuals that appeared on the monitor during the study. Small blue spheres are displayed on the user's virtual arm to indicate the locations of the vibrotactile actuators. When the user's angle errors exceeded the dead-band, the sphere representing the activated vibrotactile actuator changed from blue to white to help the user localize the vibrations. These visual motor activations were provided for all feedback conditions, even when no vibrotactile feedback was rendered. Finally, a shadow is also drawn in the scene to help the user perceive depth.

B. Experiment

We conducted a multi-session study to evaluate the effectiveness of our vibrotactile motion guidance system on motor learning. Study participants were asked to learn six arm motions with either visual (V) or visual and vibrotactile (VVT) motion guidance over the course of four learning sessions that occurred on four consecutive days of testing. Subjects returned for a follow-up retention session four days after the last learning session to evaluate how well they remembered the six motions. Participants gave written consent prior to the study, and experiment protocols were approved by the University of Pennsylvania Office of Regulatory Affairs. Twenty-six subjects (11 males, 15 females) participated in this study. Ages ranged from 18 to 49 with a mean of 23.2 years. All participants were right handed.

1) Motions Tested—Each subject was asked to learn two groups of motions (A and B), where each group contained a 1DOF motion, a 2DOF motion, and a 3DOF motion, for a total of six motions (A1, A2, A3, B1, B2, B3). Each group contained unfamiliar motions of comparable difficulty according to ratings obtained in pilot tests. A short description of the motions is provided below, and Table I lists their salient characteristics. Note that the avatars shown in Table I have been rotated to enable a clear view of each motion, as indicated by the coordinate frames. Participants always viewed the avatar from behind with the torso rendered with red dots, as shown in Fig. 6. The motions were not described in any way to the subjects prior to or during the study to prevent them from associating these motions with other previously learned movements. Motions A1 and B1 were the 1DOF motions, where the upper arm remained relatively still, and the forearm rotated about a

single axis. A1 resembled the motion of a bicep curl, and B1 resembled a side sweeping motion where the forearm moved left and right. The speeds of the motions were aimed at matching the speeds of exercises conducted by physical therapists. Motions A2 and B2 were 2DOF motions, requiring the subject to move their hand in a precise trajectory within a vertical plane while keeping the upper arm relatively stationary. For A2, the subject was required to make a figure similar to a capital letter “B” rotated 90° counterclockwise. B2 corresponds to the motion a musical conductor makes for 3/4 time, which involves making a right triangle shape with the hand. Motions A3 and B3 were categorized as 3DOF motions because they required both the upper arm and forearm to span a greater volume of space simultaneously in all directions. A3 involved rotating the arm in a backward motion, similar to a backstroke, while B3 entailed rotating the arm in a forward throwing-like motion. Each motion was approximately 7 s long, but speeds were not constant. The precise trajectories used in the study were all prerecorded by an experimenter using the Kinect, and their endings were subtly adjusted to ensure connectivity and smoothness when repeated.

Protocol: This study consisted of calibration, practice, learning, probe, task load survey, and retention phases, which are described in detail below. On the first day of participation, subjects performed the calibration, practice, learning, probe, and task load survey phases. The following three days of testing followed the same format with only the practice phase omitted, and the final fifth day of testing consisted only of a modified calibration phase and the retention phase.

Calibration: The vibrotactile arm bands were placed on the bicep and wrist of the subject’s dominant arm. The subject stood approximately 2 m away from the computer monitor and the Kinect sensor. A short calibration routine was completed to locate the user, and the user was given time to move around and familiarize themselves with the graphical environment and how the system was tracking their motions. The vibrotactile actuators were activated individually to allow the user to experience the vibrotactile feedback and to ensure that all motors functioned properly.

Practice: Before starting the first day of learning trials, participants attempted to track a practice motion with only visual feedback. The details of the visual feedback modality were explained to the user, including the shadows and the visuals of the vibrotactile actuators. Subjects were instructed to keep their hand in the orientation that appeared on screen. Then, the experimenter manually adjusted the deadband to describe the adaptive nature of the system. The subject was allowed to practice tracking the practice motion (which was different from those used in the study) for as long as they desired. After the subject was comfortable with the visual guidance, the vibrotactile feedback was activated to allow the subject to feel the vibrations they would encounter during the VVT feedback mode. Subjects were allowed to practice with the system for as long as they desired under both feedback conditions. Subjects typically chose to practice for only a few minutes. They were instructed to indicate to the experimenter when they were ready to begin the experiment. Subjects were also given an opportunity to take a break prior to beginning the experiment.

Learning: For each day's learning phase, subjects completed two sessions in which they tried to learn a set of motions (A or B) with one of the two feedback modalities (V or VVT). The pairing of motion group and feedback type was kept constant for each subject and was balanced across subjects. During a session, subjects completed four sets of 1-min trials to learn each of the three motions in the group, resulting in a total of 12 1-min trials. The timed trials were presented in pseudo-random order, completed in triplets before repetition (e.g., A3-A1-A2, A1-A3-A2, A1-A2-A3, A2-A3-A1). We will refer to the data collected during this period as the Learning Trials. Subjects were allowed to rest between trials for any duration of time, but they were not permitted to remove the arm bands.

Probe: We wanted to understand whether the availability of vibrotactile feedback during learning affected how well a subject could perform each motion from memory. Thus, at the end of each learning session (V or VVT), the subject was asked to perform five repetitions of each of the three motions learned during that session without any feedback. The only visuals provided were the visual representation of the subject's own motions. We will refer to the data from these trials as the Probe Trials.

Task Load Survey: After probe data collection, the subject was asked to complete a NASA Task Load Index (TLX) questionnaire [38] to obtain insights into the overall workload required to complete the task for that particular learning session. The NASA TLX asks subjects to rate the overall mental and physical effort required to complete the task, the perceived level of temporal effort or time pressure, their frustration, and their own performance during the task. Although there are some limitations of estimating cognitive load from a subjective evaluation, the NASA-TLX has been shown to have good reliability and validity in estimating cognitive effort [39]–[41].

After the subject finished all steps for their first learning session (V or VVT), the learning, probe, and task load survey phases were repeated for the remaining feedback modality. Completion of these three phases for both feedback modalities required about 45 min. The subject then returned for three additional days of training and testing; each day they completed the calibration, learning, probe, and task load survey phases for each set of motions and feedback conditions. The order in which the feedback conditions were presented alternated each day to reduce order bias.

Retention: On the fifth and final day of the experiment, subjects completed a retention phase to test whether feedback condition affected how well they remembered the motions after an extended period of rest (four days). The participant was instructed to perform from memory 10 repetitions of each of the six motions learned over the preceding four days (without any form of reminder before initiating the movement and no feedback during the movement). Similar to the Probe phase, only a visual representation of the subject's own motions was provided. We refer to these trials as the Retention Trials.

Lastly, participants were asked to complete a short questionnaire to record their preferences about the feedback conditions and their general comments on the experiment. This final day of testing took approximately 20 min to complete, and subjects were compensated \$50 for their participation.

C. Data Analysis

The main variable of interest in this study was the rms arm angle error across each repetition of the specified motion. Errors for the first and last iteration from each 1-min trial were discarded to ignore start-up transients and incomplete movements. For the Probe and Retention Trials, the subject's velocity of motion varied considerably. Hence, the desired trajectory was re-sampled at a rate matching the subject's recorded motion, and the rms joint angle error for each sample was then calculated. Results were analyzed and compared using repeated measures analysis of variance (ANOVA). Learning and probe trial data were analyzed separately, each with four within-subjects factors (feedback condition, motion difficulty, day of testing, and arm segment), and retention trial data were analyzed with three within-subjects factors (feedback condition, motion difficulty, and arm segment) because there was only one day of retention data collection. We use $\alpha = 0.05$ to determine significance unless noted otherwise and report all effect sizes using the η_p^2 metric. Bolded rows in Tables II–V signify $p < \alpha$.

III. Results

A. Learning Trials

Fig. 7 shows the results of the learning trials, and Table II summarizes the statistically significant factors and interactions from the ANOVA. Overall, feedback condition was found to have a significant main effect on rms angle error. The average rms angle error for the motions learned with VVT guidance was smaller ($15.7^\circ \pm 6.5^\circ$) than the average error for the motions learned with V feedback ($17.1^\circ \pm 6.4^\circ$). In addition, the main effects of motion difficulty and arm segment were found to be significant; these results were expected because the three levels of Motion Difficulty (1DOF, 2DOF, 3DOF) varied in range of motion, speed, and joint movement. The fourth factor (day of testing) was also found to have a significant main effect, indicating that the measured angle errors differed over the four days of testing; motion errors steadily decreased.

Several interactions were also found to be significant, as listed in Table II. Because the goal of this study was to evaluate the differences in performance between feedback conditions, we will focus on the interactions that involved the factor of feedback condition. The significant interaction of Feedback*Motion Difficulty, which can be seen in Fig. 8(a), shows that the addition of vibrotactile feedback affected the angle errors for the 1DOF motions, but not the 2DOF and 3DOF motions. Post-hoc tests using a Bonferroni correction ($\alpha = 0.017$) shown in Table III support this finding. Four of the six motions did not require much upper arm movement, therefore it was not surprising to see an interaction between Feedback and Arm Segment [Fig. 8(b)], where the addition of vibrotactile feedback had a larger effect on the forearm's angle errors than on the upper arm's. The ANOVA also showed two significant three-way interactions. When examining the Feedback*Motion Difficulty*Arm Segment interaction [Fig. 8(c)], it is evident that the vibrotactile feedback had a greater effect on reducing the forearm angle errors versus upper arm angle errors of the 1DOF motions. This pattern most likely stems from the motions themselves, as the upper arm had minimal movement for the 1DOF and 2DOF motions compared to the 3DOF motion. Lastly, when vibrotactile feedback was applied, errors were reduced a greater amount on Day 4 than

on previous days for the 1DOF motions and 3DOF motions, while the effect of feedback is negligible for the 2DOF motions [Fig. 8(d)], which supports the Motion Difficulty*Day*Feed-back interaction.

B. Probe and Retention

1) Probe Trials—The Probe Trials were analyzed to determine whether immediate retention of the motions was affected by the feedback condition. A plot of the average rms errors for the Probe Trials can be seen in Fig. 9, and statistically significant ANOVA results are shown in Table IV. Feedback condition did not have a significant effect on joint angle error, but the main factors of Motion Difficulty, Day, and Arm Segment did have significant main effects. Only the Motion Difficulty*Arm Segment and Day*Arm Segment interactions were found to be significant.

2) Retention Trials—Analysis of the Retention Trial data similarly found that feedback had no significant effect on the subjects' ability to perform the motion accurately after four days of rest. Fig. 10 shows a plot of the average rms joint angle errors for each of the motions during the retention trials. Subjects' performance varied as indicated by the large error bars, and no consistent pattern was found. Again, significant main factors of Motion Difficulty and Arm Segment were observed and a two-way interaction between Motion Difficulty*Arm Segment was found. Statistically significant factors are listed in Table V.

C. Workload and Survey Responses

The average workload recorded from the NASA TLX survey was calculated each day for each subject, as shown in Fig. 11. A repeated measures ANOVA was conducted to determine if there was a significant difference in workload between the feedback conditions. Overall, feedback condition had a significant effect on the subjects' reported workload ($F(1, 25) = 6.53$, $p = 0.017$, $\eta_p^2 = 0.21$), where the reported workload levels were on average slightly higher for vibrotactile feedback sessions (VVT) than for visual only feedback sessions (V). The reduction in workload over days was also statistically significant ($F(3, 75) = 10.30$, $p < 0.0001$, $\eta_p^2 = 0.29$).

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. Subjects generally agreed that the visual feedback accurately reflected their own motions (5.5 ± 0.8) and agreed that it was easy to see the wireframe arm (5.1 ± 1.3). The subjects felt that the motions in the two groups (A and B) were of equal difficulty (5.8 ± 1.0). When rating the tactile feedback, subjects did not appear to notice the graded magnitudes of vibration feedback, as they slightly disagreed with the statement that some tactile actuators were stronger than others (3.8 ± 2.1), though subjects were also more neutral to the suggestion that the feedback could have been stronger (4.3 ± 1.1). Subjects only slightly agreed with the statement that the tactile feedback was guiding them in the correct direction to achieve maximum accuracy (4.9 ± 1.6). Finally, 18/26 subjects preferred the combination of visual and vibrotactile feedback over vision alone; the average response indicated a slight preference for the visual and vibrotactile feedback at 4.9 ± 1.6 , where 1

indicated a strong preference for visual feedback and 7 a strong preference for visual and vibrotactile feedback.

IV. Discussion

This paper presents one of the first studies aimed at testing whether a tactile motion guidance system can help individuals learn and remember new arm trajectories. The conducted study showed that augmenting visual feedback with vibrotactile feedback through our low-cost (~\$216 total cost for parts), wearable motion guidance system helped users reduce their motion errors as they learned and practiced 1DOF arm motions. These findings are in agreement with those of [7]. Arm motions of varying complexity were tested, and vibrotactile feedback did not have a significant effect on 2DOF and 3DOF motions. However, the benefits observed with the 1DOF motions demonstrate the promise this type of system may have in assisting stroke patients with severe deficits, who focus on improving simple movements. Interestingly, the benefits of the vibrotactile cues during learning did not translate to any differences in the subject's ability to reproduce the movement without feedback immediately or later on. The approach of tactile motion guidance has high appeal, but the design space for such systems is enormous; this section aims to dissect and interpret our results for broad utility.

A. Factors Influencing Perception of Tactile Feedback

One overarching hypothesis, consistent with the results of the TLX survey data, is that the vibrotactile feedback was difficult for subjects to interpret, particularly for high-DOF motions. We present four aspects of the study and the system that may have required effort to interpret.

1) Simultaneous, Multi-Segment Feedback—Our findings differed from those of Sienko *et al.* [16], who found that vibration feedback was more effective for complex motions. One key difference is that although trunk sway is a multi-DOF motion, there is only one main body segment that the user must control. The motions in our study required control of multiple limb segments, making the feedback potentially more complex and difficult to interpret. One aspect of the vibrotactile feedback that may have increased cognitive effort is whether the subject had to detect vibrations on both the upper arm and the forearm simultaneously. The 1DOF and 2DOF motions principally involved moving the forearm, with only small movements of the upper arm. Therefore, the majority of the vibration feedback was applied to the forearm, and subjects were able to focus their concentration on one arm segment. In contrast, both arm segments moved a considerable amount for the 3DOF motions, resulting in more instances of simultaneous arm segment feedback, as shown in Table VI.

2) Number of Vibration Actuators Used—A second factor that we examined was the number of different motors that a subject had to recognize. The environment of our study differs from other work that has shown that users are able to distinguish between different patterns of vibration [23], [24] in a static, controlled situation. Pattern recognition of vibrotactile sensory substitution for manipulation tasks does not require users to rapidly interpret varying patterns, whereas our application emphasized the ability of subjects to

quickly localize spatially changing vibrations. If more motors were active for a certain motion, subjects may have found it challenging to process the feedback and react accordingly. Table VII shows the average number of vibration actuators activated for the different motions and arm segments. The 3DOF motions resulted in a wider variety of directional errors, involving a greater number of vibration actuators and requiring the user to spend more effort determining which motor was active. In contrast, because a 1DOF motion moves in a single plane, the user's errors were more likely to be consistent in direction, allowing subjects to learn to localize only one or two motors and quickly adjust their motions.

Duration of Vibration Stimulus: Although the vibrotactile feedback did not strongly reduce rms errors for the 2DOF and 3DOF motions, it appears that subjects were beginning to record smaller motion errors with the presence of vibrotactile feedback when learning the 3DOF motions at the end of the study [Fig. 7, Fig. 8(d)]. Though not significant, an interaction between Feedback*Day for the 3DOF motion approached significance ($p = 0.06$). One aspect of the vibration feedback that may have caused this difference is the duration of the vibration stimuli. When a vibration motor is activated, a subject first has to realize the vibration is occurring, then deduce the location of the stimulus and adjust their motion accordingly while continuing to follow the desired trajectory. The human brain can take several hundreds of milliseconds or more to process the tactile information alone. A shorter vibration stimulus would make it difficult for users to either detect the vibration, or more importantly, to react to the stimulus. This is similar to findings that demonstrated reaction times and perception levels of low vibration deteriorate when the body is in motion [5]. When examining this hypothesis (Fig. 12), we found that the average duration of the vibration stimuli on the forearm was smaller for the 2DOF motions than for the 1DOF and 3DOF motions on the first day of learning trials. We believe the first day was critical to the user's ability to understand and follow the trajectories and begin to understand the tactile feedback loop. With short bursts of vibration, subjects may have had a particularly difficult time utilizing the vibrotactile feedback for the 2DOF motions.

3) Visual Occlusion—Visual occlusion may also have influenced the effectiveness of the vibrotactile feedback. There were two different types of visual occlusion that occurred in this study. First, there is occlusion of the virtual arm. For some of the motions, the orientation of the forearm was occluded by the upper arm, preventing subjects from being able to determine how to precisely position their forearm based on visual feedback alone. Several subjects noted that they felt the advantages of the vibrotactile feedback were most prevalent when vision of the virtual arm was obscured and they had to rely on the vibrotactile guidance to correct their movements. Another source of visual occlusion was the occlusion of the blue/white dots that mimicked the activation of the vibrotactile motors. These visuals were available in both feedback conditions, and subjects commented that detection of the white dots allowed them to know when their arm was positioned incorrectly, particularly in the V feedback mode. If the visualization of a white dot was obscured by the other virtual arm segment, subjects could be unaware that their arm was in the wrong orientation without vibrotactile feedback, leading to smaller errors for the VVT condition.

B. Retention Trials

The ultimate goal of our system is to enable users to perform motion trajectories more accurately. In this study, providing vibrotactile cues to correct motion errors over the course of four days of learning did not significantly reduce subjects' motion errors during the retention trials that occurred four days after the last learning trial. There were several aspects of the study design that may have mitigated the long-term effects of the vibrotactile feedback.

Subjects were given four consecutive days to learn six different motions, which resulted in a total of 16 min of training time for each motion. This duration of practice may not have been enough time for a user to master a motion, particularly the more complex trajectories. A rehabilitation patient using this type of system would be expected to practice motions for hours, over the course of multiple weeks and months. It is possible that given more time to learn the motion trajectories and learn to use the tactile feedback, the vibrotactile feedback will have a more significant effect on the subjects' ability to remember and perform the motions.

Another factor that contributed to our results is that the motivation for subjects to concentrate and commit each trajectory to memory was quite low. The motions that subjects learned were meaningless; thus, it is possible that subjects did not try very hard to remember them. Qualitatively, we observed that subjects tended to simply remember the general patterns of the motions, but they had difficulty in trying to replicate the trajectories precisely. In contrast to unimpaired subjects, we expect that patients undergoing arm rehabilitation may be more motivated to use the system to learn motions, as learning the motions would directly benefit them. Our system is currently being tested by stroke patients with arm control deficits to determine whether the vibrotactile feedback has a greater effect on this target population.

Subjects also provided post-study observations that enabled some insight into why vibrotactile feedback had no effect on their long-term performance. Similar to the hypothesis from Sigrist *et al.* [7], some subjects felt that while the vibrotactile feedback helped to make fine corrections in the movement, having to concentrate on these fine details prevented them from learning the overall motion. These comments align with findings from other related work by Pomplun *et al.* [42] who studied arm movement initiation; they found that subjects were better able to replicate a motion when observing the motion as a whole and then repeating it, rather than attempting to imitate the motion while observing it. Although vibrotactile feedback may help users reduce motion errors during the learning process, better retention may result from a teaching method that combines the benefits of real-time feedback with the opportunity for subjects to practice and receive performance feedback on the same motion with no concurrent visual or vibrotactile cues.

C. System Limitations

The StrokeSleeve system tracks a user's motion and provides continuous visual and vibrotactile motion guidance; however, some limitations of the system may have influenced our results.

Unfortunately, the Kinect cannot track rotation of the subject's wrist about the forearm. Although subjects were instructed to keep their hand oriented to match what was presented on the virtual arm, subjects may have inadvertently rotated their wrist while performing the motions. Doing so changes the location of the vibrotactile actuators and results in vibration feedback that does not correlate with what was shown visually. These deviations could have confused some subjects and mitigated the potential benefits of the vibration feedback, particularly on the 3DOF motions.

In addition, we decided to place four motors around the circumference of each arm band instead of six or eight to keep the feedback simple. When the direction of a motion error vector was between actuators, the low actuator density may have resulted in vibration feedback that was less efficient at guiding their motions and somewhat misaligned with the visual feedback. As the subject responded to these types of motion errors, the neighboring actuators would have flickered back and forth, causing shorter activation times and potential confusion. These types of situations likely occurred during the 2DOF and 3DOF motions and made it more difficult for subjects to utilize the vibrotactile feedback. One potential solution would be to increase the density of actuators from four to six or eight. In addition to the actuators, modifying the feedback algorithm to include a low-pass filter and the ability to activate more than one actuator at a given moment for a limb segment may reduce the amount of flickering.

There is also a small time delay in the delivery of the vibrotactile feedback due to the rise time of the eccentric rotating mass motors, resulting in some instances where a white dot would briefly appear on screen but turn off before any vibrations could be felt. Users who observed these instances found them distracting, which may have contributed to their confusion in reacting to the vibration stimuli. The visual feedback could be adjusted to account for this delay.

Finally, other research has also shown that users become desensitized to vibration stimuli while in motion [5], but we did not account for this effect in our study. The subject's ability to detect the vibration feedback may have been further hampered by the fact that they were moving their arm at varying speeds. For the more difficult motions, which covered more physical space and had higher speeds, it is possible that users had a hard time detecting the vibration sensations.

V. Conclusion and Future Work

We have developed a low-cost vibrotactile motion guidance system and have shown that its vibrotactile cues can reduce motion errors while a user learns a simple arm motion. The vibrotactile cues had a benefit for 1DOF motions, but not the 2DOF or 3DOF motions. Interestingly, we found that the feedback did not have a significant effect on subjects' accuracy in performing the motions after four days of rest. Vibrotactile feedback in motion guidance involves a complex interaction of several variables that contribute to the subject's ability to interpret and react to the vibrotactile cues. We will continue refining our system to improve the quality of the feedback it can deliver.

A future goal is to assess the efficacy of the system in rehabilitation training of stroke patients, most of whom are older. Although the present study tested college-aged healthy adults, our system is aimed at improving more subtle spatio-temporal deficits of the impaired limb in stroke patients with mild hemiparesis (whose sensory loss is typically very minor) as well as those observed in the less impaired limb, e.g., [43], [44].

Many stroke patients are deficient in using body-based (intrinsic) spatial coordinates to plan movements, and they attempt to rely abnormally on visual feedback, without consistent success [45]. Consequently, we predict such patients may benefit from vibrotactile feedback that augments the salience of body-based coordinates. In addition, although stroke may be associated with cognitive and/or memory deficits, we have previously found that these participants have little trouble understanding the relatively simple task instructions for similar movement imitation tasks [45]. To this end, a follow-up study to assess the performance of stroke patients and age-matched controls is currently underway.

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Biographies

Karlin Bark received the B.S. degree from the University of Michigan, Ann Arbor, MI, USA, in 2003, and the M.S. and Ph.D. degrees in mechanical engineering from Stanford University, Stanford, CA, USA, in 2005 and 2009, respectively. She completed a Postdoctoral Research Fellowship at the University of Pennsylvania, Philadelphia, PA, USA, during 2010–2012 in the Penn Haptics Group.

She is currently a Scientist at the Honda Research Institute, Mountain View, CA, USA. Her research interests include haptics, human–machine interaction, and robotics.

Emily Hyman received the B.S. and M.S. degrees in systems engineering from the University of Pennsylvania, Philadelphia, PA, USA, in 2014.

She is currently working at Epic, Verona, WI, USA. She worked in the Penn Haptics Group during the summer of 2012 as part of the Rachleff Scholars Program.

Frank Tan received the B.S.E. degree in bioengineering and the M.S.E. degree in robotics from the University of Pennsylvania, Philadelphia, PA, USA, in 2013.

He currently works as an Analyst in the Corporate Finance and Investment Banking group at Cushman & Wakefield, New York City, NY, USA. Formerly, he was a Research Assistant in the Penn Haptics Group from 2010 to 2013. His research interests include haptics, human-machine interaction, and assistive and rehabilitative technology.

Elizabeth Cha received the B.S. degree in biomedical engineering and computer science from Johns Hopkins University, Baltimore, MD, USA, in 2011, and the M.S. degree in robotics from Carnegie Mellon University, Pittsburgh, PA, USA, in 2014. In 2014, she also completed a research fellowship at the Learning Algorithms and Systems Laboratory at École Polytechnique Fédérale de Lausanne. She is currently a Ph.D. degree student in the Interaction Lab, University of Southern California, Los Angeles, CA, USA.

Her research interests include human-robot interaction, manipulation and assistive technologies.

Steven A. Jax received the B.A. degree in psychology from the University of Minnesota, Minneapolis, MN, USA, in 1999, and the Ph.D. degree in psychology from Pennsylvania State University, State College, PA, USA, in 2005.

He has been employed at Moss Rehabilitation Research Institute, first as a Postdoctoral Fellow and now as an Institute Scientist. Work in his Perceptual-Motor Control Laboratory investigates how cognitive and perceptual processes affect movement production in healthy and stroke populations. He has received grants from the National Institutes of Health and the Albert Einstein Society.

Laurel J. Buxbaum received the B.A. degree from the University of Pennsylvania, Philadelphia, PA, USA, in 1982, and the Psy.D. degree from Hahnemann University, Philadelphia, PA, USA, in 1988. She completed a Postdoctoral Research Fellowship at Moss Rehabilitation Research Institute and the University of Pennsylvania in 1994.

She is currently Professor of Rehabilitation Medicine at Thomas Jefferson University and Director of the Cognition and Action Laboratory at Moss Rehabilitation Research Institute, Elkins Park, PA, USA. She has received numerous grant awards from the NIH and James S. McDonnell Foundation to study action in healthy and stroke populations. She is a recent Associate Editor of the journal *Cognition* and current Associate Editor of *Cortex*.

Prof. Buxbaum is the recipient of the Widener University Graduate Award for Excellence in Professional Psychology.

Katherine J. Kuchenbecker (S'04–M'06) received the B.S., M.S., and Ph.D. degrees in mechanical engineering from Stanford University, Stanford, CA, USA, in 2000, 2002, and 2006, respectively. She completed a Postdoctoral Research Fellowship at the Johns Hopkins University, Baltimore, MD, USA, in 2006–2007.

She is currently the Skirkanich Assistant Professor of Innovation in Mechanical Engineering and Applied Mechanics at the University of Pennsylvania, Philadelphia, PA, USA. Her research centers on the design and control of haptic interfaces and robotic systems, and she directs the Penn Haptics Group, which is part of the General Robotics, Automation, Sensing, and Perception (GRASP) Laboratory.

Prof. Kuchenbecker was the recipient of a 2009 National Science Foundation CAREER Award, the 2008 and 2011 Citations for Meritorious Service as a Reviewer for the IEEE Transactions on Haptics, and the 2012 IEEE Robotics and Automation Society Academic Early Career Award.

Fig. 1. StrokeSleeve tactile motion guidance system consists of a Microsoft Kinect to track the user's motions, a computer screen to provide visuals of the measured and desired motions, and a pair of vibrotactile arm bands to indicate motion errors.

Fig. 2.
Plastic caps (in white) are used to attach four vibrotactile actuators around the circumference of an arm band with equal spacing.

Fig. 3.

(a) Frequency and (b) amplitude of vibration actuators as applied voltage increases.

Fig. 4.

Sample schematic illustrating the vectors used to calculate joint angle errors and which actuator is used to guide the user. In this example, to guide the user from their measured forearm orientation ${}^N\vec{P}_{F,meas}$, to the desired orientation, ${}^N\vec{P}_{F,des}$, the motor represented by the vector ${}^N\vec{P}_{m,2}$ would be activated. This motor is colored in white to indicate that it is active.

Fig. 5.

Voltage commanded to the vibrotactile actuators as a function of the angle error outside the deadband. When the angle error was within the deadband, zero voltage was applied.

Fig. 6.

Annotated screenshot of the visuals provided. User's own motions were displayed with an avatar. Wireframe arm, whose diameter was proportional to the deadband, indicated a desired trajectory. Users were instructed to stay within this region. Small spheres representing the vibrotactile actuators and a shadow on the virtual floor provided additional cues.

Fig. 7.

Average rms angle errors recorded during the learning trials for all subjects, grouped by motion difficulty (1DOF, 2DOF, 3DOF). Red and blue lines represent the visual and vibrotactile (VVT) and visual only (V) conditions respectively. Upper arm and forearm errors are shown separately. Overall, errors recorded under the VVT condition were significantly smaller ($p < 0.01$) than those recorded with the V condition.

Fig. 8.

Plots displaying significant interactions involving feedback condition for the learning trials. Significant interactions ($p < 0.05$) were found between (a) motion difficulty and feedback condition, (b), arm segment and feedback condition, (c) motion difficulty, arm segment, and feedback condition, and (d) motion difficulty, day of testing, and feedback condition.

Fig. 9.

Average rms angle errors recorded during the probe trials for all subjects, grouped by motion difficulties (1DOF, 2DOF, 3DOF). Red and blue lines represent the Visual and Vibrotactile (VVT) and Visual only (V) conditions, respectively. Upper arm and forearm errors are shown separately. Feedback condition did not have a significant effect on the rms angle errors.

Fig. 10.

Average rms angle errors recorded during the retention trials for all subjects, grouped by motion difficulties (1DOF, 2DOF, 3DOF). Red and blue lines represent the Visual and Vibrotactile (VVT) and Visual only (V) conditions respectively. Upper arm and forearm errors are shown separately. Feedback condition did not have a significant effect on the rms angle errors.

Fig. 11.

Boxplot of reported workload for all subjects across the four days of learning. On average, subjects reported a higher workload with the VVT condition as compared to the V case, although workload decreased over the course of the study. Line indicates the median, the box shows the span of the second and third quartiles, whiskers show the range up to 1.5 times the inter-quartile range, and x's mark outliers.

Fig. 12.

Average duration of vibrotactile stimuli for the different motions for all subjects.

TABLE I

Characteristics of Motions Tested^{***}

Motion [*]	A1	A2	A3	B1	B2	B3
DOF	1	2	3	1	2	3
Duration (s)	6.6	6.6	7.6	6.3	6.9	7.5
Range of Motion ^{**} (cm)						
Upper Arm						
Horizontal	2.2	7.1	16	10	14	17
Vertical	2.0	3.7	39	2.2	5.1	47
Depth	2.5	10	29	12	13	44
Forearm						
Horizontal	22	57	64	66	49	21
Vertical	36	26	91	10	29	105
Depth	17	25	53	26	16	61
Avg. Angular Speed (°/s)						
Upper Arm	4	10	28	10	12	38
Forearm	29	47	47	45	39	44

* Green lines represent the trajectory followed by the wrist, and the black lines represent the trajectory followed by the elbow.

** Estimated ranges of motion are based on the arm length of the average female.

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Light, medium, and dark gray shading indicates relative low, medium, and high ranges respectively.

TABLE II

Selected Statistical Results for Learning Trial rms Angle Error

Factors	F-ratio	p-value	η_p^2
<i>Main Factors</i>			
Feedback	$F_{(1,25)} = 7.9$	0.01	0.24
Difficulty	$F_{(1.5,37.3)} = 356.6$	<0.001	0.93
Day	$F_{(3,75)} = 167.4$	<0.001	0.87
Arm Seg.	$F_{(1,25)} = 2.3$	<0.001	0.95
<i>Interactions</i>			
Feedback*Difficulty	$F_{(1.6,40)} = 4.9$	0.02	0.16
Feedback*Day	$F_{(1.6,48.8)} = 2.4$	0.10	0.09
Feedback* Arm Seg.	$F_{(1,25)} = 5.3$	0.03	0.17
Difficulty*Arm Seg.	$F_{(1.8,44.2)} = 177.8$	0.00	0.88
Day*Arm Seg.	$F_{(3,75)} = 10.4$	0.00	0.29
Feedback*Diff.*Day	$F_{(4.1,102.7)} = 2.6$	0.04	0.10
Feedback*Diff.*Arm Seg.	$F_{(1.4,35.6)} = 4.6$	0.03	0.15

TABLE III

Selected Post-Hoc Statistical Results for Learning Trial rms Angle Error

Factors	F-ratio	p-value	η_p^2
<i>1DOF Motion</i>			
Feedback	$F_{(1,25)} = 18.1$	<0.001	0.42
Day	$F_{(3,75)} = 59.9$	<0.001	0.71
Arm Seg.	$F_{(1,25)} = 429.3$	<0.001	0.95
Feedback*Day	$F_{(3,75)} = 3.5$	0.06	0.12
Feedback*Arm Seg.	$F_{(1,25)} = 22.7$	<0.001	0.48
Day*Arm Seg.	$F_{(3,75)} = 7.9$	<0.001	0.24
<i>2DOF Motion</i>			
Feedback	$F_{(1,25)} = 0.3$	0.59	0.01
Day	$F_{(3,75)} = 107.1$	<0.001	0.81
Arm Seg.	$F_{(1,25)} = 507.4$	<0.001	0.95
Day*Arm Seg.	$F_{(3,75)} = 5.3$	<0.001	0.18
<i>3DOF Motion</i>			
Feedback	$F_{(1,25)} = 2.0$	0.17	0.08
Day	$F_{(3,75)} = 110.7$	<0.001	0.82
Arm Seg.	$F_{(1,25)} = 61.1$	<0.001	0.71
Feedback*Day	$F_{(3,75)} = 2.6$	0.06	0.10
Day*Arm Seg.	$F_{(3,75)} = 3.1$	0.03	0.11

TABLE IV

Selected Statistical Results for Probe Trial rms Angle Error

Factors	F-ratio	p-value	η_p^2
<i>Main Factors</i>			
Feedback	$F_{(1,25)} = 0.0$	0.99	0.00
Difficulty	$F_{(1,4,35,4)} = 99.9$	<0.001	0.80
Day	$F_{(3,75)} = 30.8$	<0.001	0.55
Arm Seg.	$F_{(1,25)} = 187.6$	<0.001	0.88
<i>Interactions</i>			
Difficulty*Arm Seg.	$F_{(2,50)} = 30.1$	<0.001	0.55
Day*Arm Seg.	$F_{(3,75)} = 3.5$	0.02	0.12

TABLE V

Selected Statistical Results for Retention Trial rms Angle Error

Factors	F-ratio	p-value	η_p^2
<i>Main Factors</i>			
Feedback	$F_{(1,25)} = 1.3$	0.26	0.05
Difficulty	$F_{(2,50)} = 32.6$	<0.001	0.57
Arm Seg.	$F_{(1,25)} = 91.4$	<0.001	0.79
<i>Interactions</i>			
Difficulty*Arm Seg.	$F_{(2,50)} = 4.2$	0.02	0.15

TABLE VIPercent of Time Vibration Feedback was Applied (Mean $\pm$ sd)

	1DOF	2DOF	3DOF
Upper Arm Only	5.3 $\pm$ 1.7	4.9 $\pm$ 1.6	14 $\pm$ 2.3
Forearm Only	38 $\pm$ 3.7	39 $\pm$ 3.0	27 $\pm$ 3.0
Both Segments	5.8 $\pm$ 2.1	4.6 $\pm$ 1.4	22 $\pm$ 3.4

TABLE VIINumber of Vibration Actuators Activated (Mean $\pm$ sd)

	1DOF	2DOF	3DOF
Upper Arm	1.0 $\pm$ 0.2	1.1 $\pm$ 0.2	2.4 $\pm$ 0.2
Forearm	2.2 $\pm$ 0.2	3.0 $\pm$ 0.2	3.2 $\pm$ 0.2