Motor Learning using a Kinematic-Vibrotactile Mapping targeting Fundamental Movements

Troy McDaniel, Morris Goldberg, Daniel Villanueva, Lakshmie Narayan Viswanathan, Sethuraman Panchanathan

Center for Cognitive Ubiquitous Computing
School of Computing, Informatics and Decision Systems Engineering
Arizona State University
Tempe, Arizona, USA 85281

{troy.mcdaniel, daniel.villanueva, lakshmie, panch}@asu.edu, mgoldberg@ieee.org

ABSTRACT

In this paper, we present a novel approach for teaching motor skills through the use of vibrotactile stimulation. We propose a kinematic-vibrotactile mapping that targets fundamental movements (basic building blocks of human motion) using saltatory vibration patterns where vibrations are delivered and interpreted as movement through a conceptual mapping. Two conceptual mappings are explored: the "follow me" concept and the push/pull metaphor. A user study, approved by a local ethics committee, was conducted to explore how these conceptual mappings affect learnability, recognition accuracy, response time and naturalness. Results show the approach to work effectively with a combination of vibration patterns under each conceptual mapping providing the most useful design.

Categories and Subject Descriptors

H.5.2 [User Interfaces]: Haptic I/O.

General Terms

Design, Experimentation, Human Factors.

Keywords

Vibrotactile, saltation, kinematic, fundamental movements.

1. INTRODUCTION

Movement is the bridge between us and our interaction with the world around us. To interact with our environment, we manipulate objects with our hands and body; verbally communicate through tongue and lip movements; and express ourselves or convey ideas through a combination of hand and body gestures, facial expressions and eye movements in addition to verbal cues and social touch. It goes without saying, then, the importance of movement in daily life for accomplishing tasks and goals, socializing with others, and maintaining one's health through exercise. To enrich our lives, we strive to expand our set of motor skills for enhancing our health through sports and exercise; for recreational purposes, such as sports, or as an artistic outlet, such as learning a new musical instrument; or for attaining career goals. The method in which a novel motor skill is taught, and how well the pedagogy aligns with the learning style of the student, will influence how effectively and efficiently the skill is mastered.

As most people are visual learners, individual or group instruction of movement and posture is typically delivered through a combination of verbal explanation and visual demonstration [1]. Verbal cues are often used to convey a high level description of the movement, but are often difficult to parse and translate into movement [2]; even so, they are useful as a complement to visual demonstration. Upon watching a visual demonstration of a movement, students will attempt to mimic the movement by mapping it onto their frame of reference. Feedback from a trainer takes the form of verbal explanation and/or visual demonstration, focusing on improving the movement or posture in question. During this stage, trainers will often make physical contact to complement their feedback; touch cues may be used to guide movement, or shift attention to limbs or areas of the body that are moving incorrectly or are of incorrect posture.

There are several shortcomings with the aforementioned pedagogical techniques for teaching motor skills. First, consider the challenges of group instruction. When trainers are nearby, students tend to learn more effectively [1], most likely due to improved motivation and feedback, and a clear view of the movement to be learned; but with a large group of students, this isn't always possible. Physical contact is a useful complement to verbal and visual cues, but it is sparse in a group setting, and in fact difficult to provide as only a portion of limbs and joints can be engaged at any moment [2]. Moreover, learning preferences are often overlooked, creating missed opportunities. In martial arts instruction [3], it is recommended to accommodate each student's learning preference: some students learn visually through demonstration, some auditorily through discussion and some kinesthetically through practice. However, individualized instruction is often difficult to achieve in large classes. In general, one-on-one instruction offers the benefits of working closely with a trainer. However, such instruction is expensive especially over a long period of time, and is therefore not affordable for many students.

Common are situations where our visual, auditory and/or haptic modalities are overloaded or unavailable for receiving motor instructions. For example, in a group scenario, our vision and hearing can quickly become overloaded with information due to

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distractions of other students. There are numerous examples where our modalities may be unavailable for use: in many sports, such as snowboarding [4] and swimming [5], students are unable to receive real-time feedback from trainers during the activity due to the physical separation or nature of the activity; while playing a musical instrument, real-time visual and auditory feedback is difficult to provide as vision and hearing are already overloaded with information from reading music, focusing on playing and listening to the sound [6]; and lastly, visual or auditory modalities may not be useful options when instructing students with sensory or perceptual impairments affecting vision or hearing.

To address one or more of the aforementioned issues associated with traditional pedagogy of motor skills, researchers have proposed augmented and virtual reality solutions utilizing multimedia content of images, video, audio, graphics and/or haptics. Although the majority of approaches are multimodal in that they either augment traditional methods or provide a complete multimedia experience, it is useful to categorize the approaches based on the specific modality that is augmented to improve motor learning: approaches may therefore be classified under the visual, auditory, kinesthetic or vibratory modality.

1.1 Visual Modality

Motor instruction and feedback VR and AR approaches targeting our visual modality engage our sight with multimedia content including images, video, animation and/or graphics. Within this category, the most common approaches are those of virtual reality in which one-on-one instruction and feedback is simulated. Often a head mounted display is used to enable users to compare their virtual representation's movement to a virtual expert's movement to correct movement errors in real-time [7][8]. However, the bulkiness and cost of most wearable VR systems may limit practicality. Moreover, this solution is limited in situations where our visual modality is overloaded or unavailable.

1.2 Auditory Modality

The benefits of sound and music are well known for motor learning and performance. Auditory feedback while playing a musical instrument is critical for self-evaluation; and musical rhythm helps with timing in dancing and exercise. Additionally, auditory-based motor instruction and feedback AR approaches have been proposed to more directly assist with motor learning. These approaches transform kinematic and/or kinetic data into sound, where sensors, such as accelerometers [9] or force sensors [10][11], extract motion cues. Unfortunately, as with the visual modality, there are many application scenarios where hearing may be overloaded or unavailable.

1.3 Kinesthetic Modality

Kinesthetic-based motor instruction and feedback AR approaches utilize robotics, exoskeletons or haptic devices to promote motor learning or rehabilitation through haptic guidance and/or resistance. A variety of systems have been proposed, both in the context of robot-assisted motor learning [12] and haptic guidance [13][14], with much focus on motor rehabilitation. Although studies have shown the benefits of haptic guidance for acquiring new motor skills or rehabilitation, these approaches are limited by cost and portability of equipment.

1.4 Vibratory Modality

Based on previous work, described in Section 2, vibrotactile stimulation for teaching motor movements seems to offer a promising alternative to the aforementioned approaches: vibration motors are small, lightweight, and inexpensive, and engage our tactile sense, avoiding overloaded or unavailable visual or auditory modalities; in addition to bridging the gap between distally located students and teachers as found in many sports. Proposed AR approaches cover a variety of applications for sports [4][5], music playing [6][18] and rehabilitation [2][15]. Support-based approaches (in this work, referred to as instruction-based) cue students to perform movements regardless of their performance, whereas feedback-based approaches provide stimulation linked to performance with the intent to correct errors [10]. Feedback-based vibrotactile stimulation has been shown to be useful for motor learning [2][6], which should come as no surprise given the importance of feedback while mastering new motor skills (see [2]); but feedback alone is not enough during motor training as we need to know the movement to be performed (be it a novel movement, or a movement that is part of a regimen provided by the trainer). Therefore, feedback-based approaches are often combined with visual and/or auditory instruction. However, as situations may arise where our visual or auditory modalities are overloaded or unavailable, vibrotactile instruction-based approaches cannot be dismissed.

Instruction-based approaches have been largely application-specific, making proposed vibrotactile cues difficult to generalize to other domains. Further, how vibrations map to movements (i.e., the kinematic-vibrotactile mapping), and how these mappings affect perception and motor performance, has received little attention. We propose an instruction-based approach to address these two limitations. Rather than target high-level, complex movements or movements related to a specific application, we target the basic building blocks of human motion: the fundamental movements [16]. As these basic movements may be combined to create almost any human motion, our approach is general enough to be applicable to a wide variety of application domains. The details of our proposed approach and system implementation are given in Section 3 and 4, respectively, but first we provide an overview of related work in Section 2. Next, in Section 5, we present a user study, approved by a local ethics committee, in which we systematically explored the design space to discover which vibrotactile instructions are the most natural for cueing fundamental movements. Lastly, Section 6 gives possible directions for future work.

2. RELATED WORK

2.1 Feedback-Based Approaches

In general, feedback-based approaches utilize vibrotactile stimulation to communicate errors in joint angles, positions or accelerations compared to some predefined movement or posture, typically of an expert or the user's own calibration profile in the case of physical therapy. Lindeman et al. [17] proposed the TactaPack: a wearable assistive device for physical therapy that utilizes wireless, attachable modules, each with an accelerometer and vibration motor, and its own processing and power capabilities. Vibrations (which take the place of a nudge) warn of limbs exceeding (or not reaching) acceleration ranges found during the calibration stage wherein a physical therapist leads the regimen. MusicJacket [6] is a wearable system that provides vibrotactile feedback to students learning to play the violin. Specifically, vibration motors on the arms and wrists as well as the torso, provide guidance for proper bowing movement and playing posture. The Tactile Interaction for Kinesthetic Learning

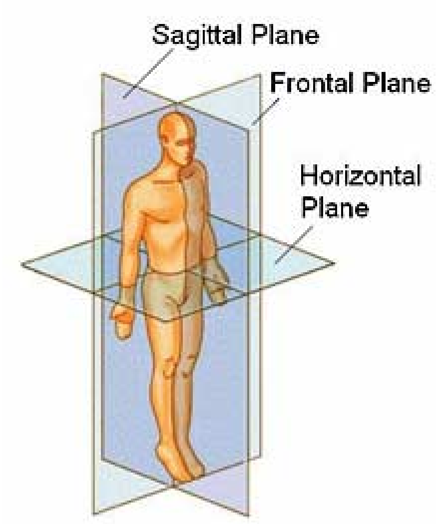

Figure 1. Sagittal, frontal and horizontal planes of the human body. Body posture shown is the anatomical position. Adapted from the Wikimedia Commons file "File:BodyPlanes.jpg".

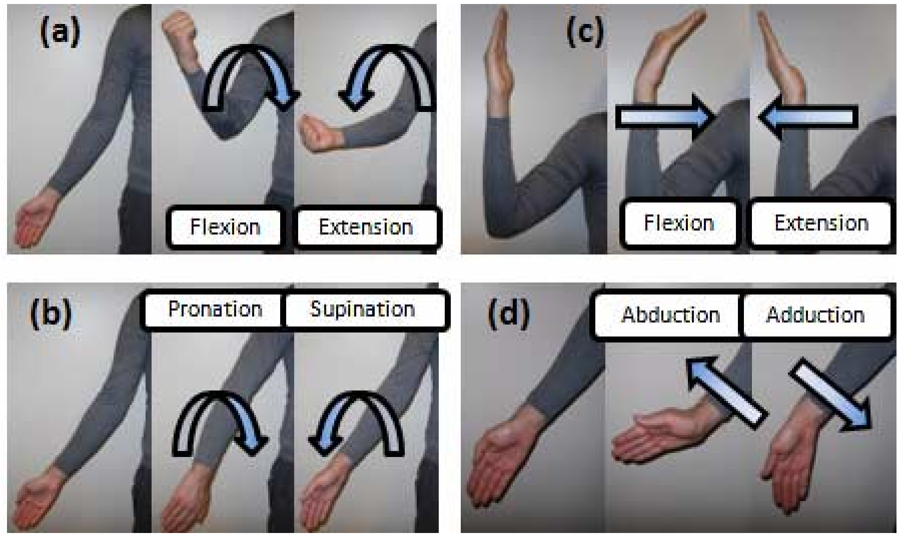

Figure 2. Visual demonstration of fundamental movements of the right arm (referred to in later sections) while in the anatomical position. (a) flexion and extension of the elbow joint; (b) rotations of the forearm; (c) flexion and extension of the wrist joint (shown in different position for visibility); and (d) abduction (radial deviation) and adduction (ulnar deviation) of the wrist joint.

(TIKL) wearable system, designed and implemented by Lieberman et al. [2], conveys which joints are in error through the location and intensity of vibrations, found based on comparisons with an expert's movement and the magnitude of error, respectively. A similar methodology is used by StrokeSleeve [15]; but unlike TIKL, which uses infrared motion tracking, StrokeSleeve uses magnetic tracking. Both TIKL and StrokeSleeve target the fundamental movements of the arm.

2.2 Instruction-Based Approaches

Instruction-based approaches communicate which movement to perform using spatio-temporal vibration patterns of varying levels of abstraction. The level of abstraction of instructions ranges from high-level ("step left foot forward", "lean forward", etc.) to low-level movements such as fundamental movements. In [5], vibrotactile pulses delivered to the left wrist of a swimmer conveyed the speed at which to swim (fast or slow when stimulation is on or off, respectively); and which arm to perform a stroke with depending upon the duration of the vibration (short or long). Mobile Music Touch (MMT) [18], developed by Huang et al., is a wearable glove that uses vibration pulses (one vibration motor for each finger) to help teach piano music subconsciously while away from the piano. Spelmezan et al. [4] proposed tactile motion instructions to enable snowboarding coaches to deliver real-time instruction and feedback to students as they are riding. Although the authors intended the instructions to be used for feedback (delivered automatically or by a coach), the cues could also be instruction-based to provide a supportive function regardless of user performance. An open response paradigm explored movements elicited from a set of vibration patterns that were gauged as useful. Subjects found single pulses to be vague, and preferred saltatory vibration patterns given their directionality. Although responses varied across participants in terms of the movement elicited by each pattern, a useful set of patterns was derived and tested under realistic snowboarding conditions. Spelmezan et al. also discovered that subjects interpreted vibrations as either pushing or pulling a limb. Lastly, in [19], we presented high-level spatio-temporal design guidelines for mapping vibrations to fundamental movements for the purpose of instruction-based motor learning. However, no formal user study was conducted to learn how design parameters affect the usefulness and naturalness of vibrotactile cues for motor learning. In the following section, we present our proposed conceptual methodology and system implementation.

3. KINEMATIC-VIBROTACTILE MAPPING

The aforementioned instruction or feedback-based approaches all facilitate motor learning through a kinematic-vibrotactile mapping. There are three stages within this mapping: (1) the design of the vibration signal to be applied to the skin; (2) the conceptual mapping of the perceived vibration signal to the movement it is intended to elicit or cue; and (3) the type of movement to be performed based on the cue. As discussed, kinematic-vibrotactile mappings have been application specific; we propose a novel, generic mapping, and shed light on several research questions through pilot testing and a formal user study.

3.1 Fundamental Movements

The human body is capable of five fundamental movements [16]: flexion, extension, abduction, adduction and rotation. Consider our posture being that of the anatomical position (see Figure 1); each fundamental movement occurs in one of three cross-sectional planes that divide the body into different halves. Flexion and extension occur within the sagittal plane about the frontal-horizontal axis. At a given joint, flexion or extension causes a decrease or increase in the joint angle, respectively. Abduction and adduction occur within the frontal plane about the sagittal-horizontal axis. Abduction is movement away from the sagittal plane, whereas adduction is movement toward the sagittal plane. Rotation occurs within the horizontal plane about the frontal-sagittal axis. Rotation of a limb toward the sagittal plane is pronation, whereas rotation of a limb away from the sagittal plane is supination. In this work, we limit movements to the right arm (see Figure 2) so that a thorough, exploratory study is feasible.

Given that we are targeting the basic building blocks of movement, this approach is intended for use by those just beginning to learn a complex movement. Typically, beginners are first taught which movements to perform, and after the student has become familiar with the movement or sequence of movements, the next goal is to perfect these movements [10]; and so, we hypothesize that imparting knowledge about which joints and structures are involved in the movement will be useful during the early stages of learning. With the addition of feedback-based instruction (see future work in Section 6), the proposed approach has the potential to scale well to users with a wide range of skill including experts. By linking real-time vibrotactile feedback with user performance, users will have the capability to master movements, and practice and self-evaluate their skill over time to retain a high degree of movement control and coordination.

3.2 Vibrotactile Stimulation

Saltation [20] is a perceptual illusion, often demonstrated by three vibration motors, spaced along a cross-section of the skin, actuated in sequence with three brief vibration pulses each. Rather than perceiving localized pulses at each motor, pulses feel as if they are spaced across the whole length of the array of motors. Saltation provides the illusion of apparent motion, which has an associated directionality, useful for motor learning applications [4][19]. For this reason, we've chosen to use saltatory vibration patterns as our form of vibrotactile stimulation. Of course, saltation isn't limited to only three motors or three pulses; spatio-temporal vibrations have many dimensions that affect perception of saltation: number of motors; motor spacing/placing; and the length, number and spacing between pulses (see [20]).

3.3 Conceptual Mapping

When mapping vibration patterns to movements, pedagogical concepts may be employed to better facilitate user understanding and learning. If certain vibration patterns naturally elicit movement without any training, teaching these concepts may not be necessary; however, it is difficult to find such vibrations given user variability and preferences. In this work, we explore two pedagogical concepts: the mimic or "follow me" concept, and the push/pull metaphor, both in the context of saltatory vibrations to cue fundamental movements—that is, our proposed kinematic-vibrotactile mapping. Our interest here is exploring how intuitive or natural these concepts are to users. A key design choice affecting the naturalness of a conceptual mapping is how the vibration motors are spaced and placed on the skin, or the configuration of motors. Given an infinitely large design space, pilot testing was done for each conceptual mapping in an effort to narrow down configurations for each fundamental movement.

3.3.1 Mimic or "Follow Me" Concept

The idea behind the "follow me" conceptual mapping is to simply follow the direction of vibration pulses as they move along a cross-section of the skin. Through pilot testing, we found that vibration directionality tangential to its assigned movement trajectory seems to be the most intuitive. For example, if we bend our arm at the elbow joint (flexion), the movement follows an arc; a vibration pattern with directionality orthogonal to our forearm would be tangential to this arc. Figure 3 (a)-(d) provides a visual depiction of configurations for each fundamental movement of the right arm, where, through pilot tests, configurations were narrowed down to those shown. These patterns were deemed the most natural, and were selected for evaluation. Below, we present observations made during pilot testing; but first, the following measurements were recorded when the system was not worn, and motors are identified using anatomical locations with respect to the arm held out in front of the user with the palm facing down: (a) elbow flexion/extension: inter-motor spacing of 2 in. (dorsal aspect to medial side) and 2.125 in. (medial side to volar aspect); (b) forearm rotations: inter-motor spacing of 2 in. (dorsal to medial side), 2 in. (medial side to volar aspect), 2.5 in. (volar aspect to lateral side) and 2 in. (lateral side to dorsal aspect); (c) wrist flexion/extension: inter-motor spacing of 1.25 in. (dorsal aspect to medial side) and 1.125 in. (medial side to volar aspect); and (d) wrist abduction/adduction: inter-motor spacing of 1.25 in. (medial side to center) and 1.375 in. (center to lateral side).

For elbow flexion/extension, saltation felt most natural when delivered to the volar aspect of the middle of the forearm or more proximal, near the elbow joint. The middle of the forearm should be avoided, however, to prevent confusion with vibrations for forearm rotations; as should more distal regions to avoid confusion with vibrations for wrist movements. For forearm rotations, saltation (conveyed by at least four motors) felt most natural anywhere on the forearm; but the middle portion is recommended to avoid vibrations for wrist and elbow movements. For wrist flexion/extension, saltation felt most natural when delivered to either side of the wrist joint (we used the medial side when the back of the hand is anterior to the palm of the hand). For any wrist movement, it is recommend to avoid placing motors across the wrist joint and onto the forearm as rotational movements will cause the forearm to move within the worn fabric, misaligning a configuration with its respective movement; in other words, if vibration patterns are to work well for any arm (or, limb, body, etc.) posture, then careful attention must be paid to spatial variations of motors as movements are performed. Also, avoid placing motors on the palm as it may be obtrusive. Lastly, for wrist abduction/adduction, saltation felt most natural when delivered to the back of the hand on or below the knuckles, where the generous surface area provides sufficient spacing between individual motors, as well as with vibrations targeting wrist flexion/extension. In general, to improve distinctness, vibration patterns targeting different fundamental movements, e.g., rotations versus elbow flexion/extension, should not share motors, and be as far apart as possible. Lastly, within a configuration, motors must be spaced such that directionality is easily perceived.

3.3.2 Push and Pull Metaphor

The push metaphor teaches us to perceive vibrotactile stimulation as "pushing" a limb; or "pulling a limb" in the case of the pull metaphor. Through pilot testing, vibrotactile stimulation that runs parallel to the limb, either across the joint that is to be articulated, or near the joint, seems to be the most intuitive. Whereas Spelmezan et al. [4] used either the push metaphor or the pull metaphor, we combine these into the push/pull metaphor, halving the needed number of motors, thereby making the system more cost effective and simplifying design and hardware. As an example, consider elbow flexion/extension: upon feeling a vibration running up the volar aspect of the forearm across the elbow joint, this vibration pattern would be perceived as pulling (or flexing) the forearm; if the vibration runs in the opposite direction, the pattern would be perceived as pushing (or extending) the forearm. A visual depiction of the configurations are shown in Figure 3 (e)-(h), and the following measurements were recorded, under the same conditions described in Section 3.3.1, and similarly presented: (e) elbow flexion/extension: inter-motor spacing of 4.25 in. (distal to center) and 2.75 in. (center to

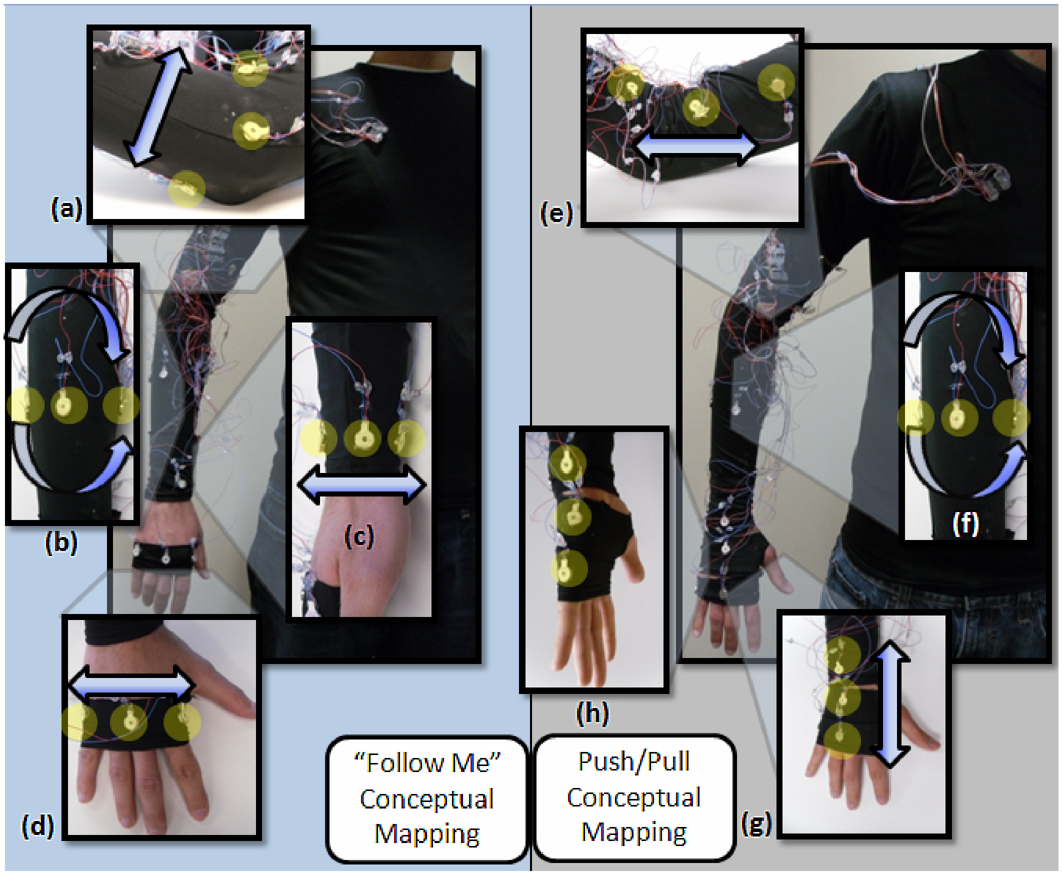

Figure 3. Vibration motor configurations (highlighted) and directionality (arrows) for "Follow Me" (left) and Push/Pull (right) conceptual mappings. Rotation pattern (f) is identical to (b), and so it uses the "follow me" rather than push/pull mapping. All movements use three motors except rotations (b) and (f) which use four motors equidistantly spaced around the forearm (the motor on the volar side of the forearm is not shown as it is occluded by the arm). For saltation, each motor vibrates for four brief pulses (with the exception of rotations, where motors vibrate for three pulses so that the total duration is reasonable) of a burst duration of 100 ms with an interstimulus interval of 60 ms. Moreover, before each pattern begins, a longer pulse (burst duration: 500 ms; interstimulus interval: 200 ms) is given at the starting motor to help capture the user's attention. This gives a total duration of 2.56 seconds for each pattern except rotations, which are of length 3.04 seconds. Rotations have a longer duration given that five motors in total are actuated (the vibration pattern comes full circle, ending on the starting motor).

proximal); (f) forearm rotations: same as (b); and for both (g) wrist flexion/extension and (h) wrist abduction/adduction, motor spacing measurements cannot be made, except for when the system is worn, as motors are each attached to separate garments; in any case, however, we can make measurements between motors of these two groups based on which motors share sections of garments: distal motors have a spacing of 1.625 in., center motors have a spacing of 1.75 in., and proximal motors have a spacing of 1.375 in.

For elbow flexion/extension, saltation felt most natural when delivered to the volar aspect of the arm across the elbow joint, with the center motor on the elbow joint. Motors should be generously spaced apart so that when the arm is fully flexed, the vibration pattern for extension may still be easily perceived. Vibration patterns for rotations were most intuitive when explained and delivered under the "follow me" concept (see previous subsection), so no push/pull version is proposed. For wrist flexion/extension, saltation felt most natural when delivered to either the palm or back of the hand, but it is recommended to avoid the palm; and as described before, for wrist movements, motors should not be placed posterior to the wrist joint (and hence onto the forearm) to avoid complications arising from forearm rotations. For wrist abduction/adduction, saltation felt most natural when delivered to the lateral side of the hand when the back of the hand is anterior to the palm.

4. SYSTEM IMPLEMENTATION

Figure 4 depicts the hardware of the system. The sleeve is part of a compression shirt (Men's medium; 84% polyester, 16% spandex). A LilyPad Arduino (ATmega328) microcontroller is powered using a LilyPad LiPower and a 2000 mAh Polymer Lithium Ion battery. To deliver power, stranded wires are used to reduce resistance. Thin, flexible, solid core wires are used to trigger motors. Wires are slack to provide flexibility when altering configurations, and to enable subjects to easily move while wearing the system. The microcontroller controls vibration motors (pancake motors; 150 Hz), attached with a small dab of hot glue that is easily removed when spatially altering motors. Motors are not directly connected to the microcontroller, but instead, are connected through nested 8-bit address latches (model#: 74HC259N). Within our implementation, latches are nested for two levels, enabling one microcontroller to support over 200 motors. Between a latch and a motor (each latch supports 7 motors) is a driver (Hi V & A Darlington Transistor Array; model#: ULN2004ANE4).

The firmware stored on the microcontroller was developed using the Arduino development environment. The firmware stores vibration patterns (a sequence of motor actuations of specific timings), triggered when received over Bluetooth. These commands are sent wirelessly from a GUI-based application that was developed using Visual C#. The GUI enables users to connect to the microcontroller, actuate motors individually or from pre-defined patterns, and start/stop a timer for recording response times.

5. EXPERIMENT

Aim: The purpose of this study is to explore the naturalness of the proposed kinematic-vibrotactile mapping; in particular, we wish to explore how the "follow me" concept and push/pull metaphor affect naturalness. Naturalness is primarily investigated through subjective feedback, but learning rate, recognition accuracy, and response time may also shed light on the usefulness of the conceptual mappings. It is important to note that the intuitiveness of a conceptual mapping is closely linked to motor spacing and placement (configuration); we've accounted for this through extensive pilot testing to find the most useful and natural configurations for each fundamental movement of the two conceptual mappings. Moreover, we cannot assume that vibration patterns, after being learned in one posture, will generalize to different postures. Ideally, however, we'd prefer *posture-free* vibration patterns that generalize well to other postures after being mastered in one training posture. To this end, we explore how well the proposed vibration patterns generalize to novel postures (various arm postures).

Subjects: The experiment involved 20 subjects, all Arizona State University students, divided between two conditions. The "follow me" condition involved 8 males and 2 females (age range: 19 to 27; mean: 24); and the push/pull condition also involved 8 males and 2 female (age range: 20 to 34; mean: 25). No subjects had motor or tactile impairments.

Procedure: Subject information including age, sex, height and weight was collected. The experiment was briefly explained to participants, after which they donned the wearable system, depicted in Figure 4 with configurations depending on their assigned condition (see Figure 3). The experiment consisted of three phases: a familiarization, training, and two-part testing phase. The experimenter explained the randomly assigned condition, which was either the "follow me" or push/pull conceptual mapping. During the entire study, with the exception of the second part of testing, subjects were asked to remain standing with their arms by their sides (training posture). During the familiarization phase, each vibration pattern of the assigned conceptual mapping was sequentially presented; before each presentation, the experimenter demonstrated the movement and explained the stimulation, relating it to its conceptual mapping. To avoid confusion, layman terminology (see Table 2) was used to specify fundamental movements: for example, 'wrist up' rather than 'wrist extension'. For simplicity, since wrist abduction/adduction is depended upon the posture of the hand with respect to the sagittal plane, they are taught in posture B (see

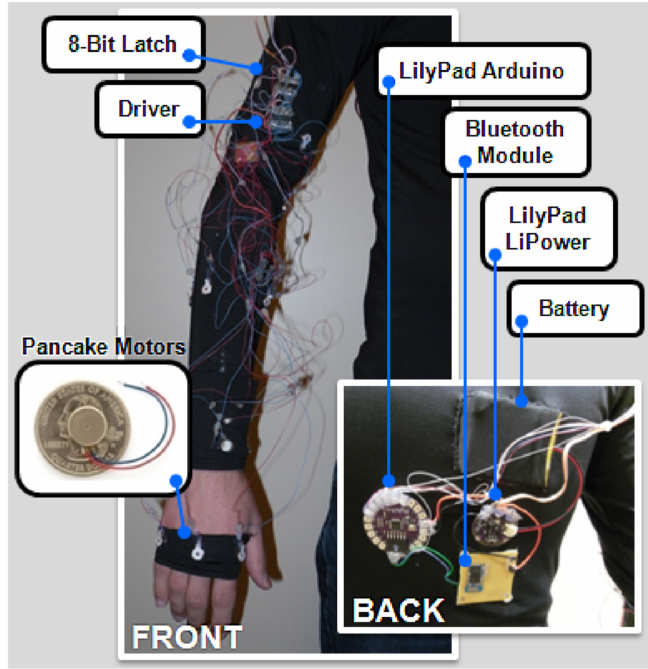

Figure 4. Hardware of system implementation depicting microcontroller, power supply, wireless communication module, actuators and other components.

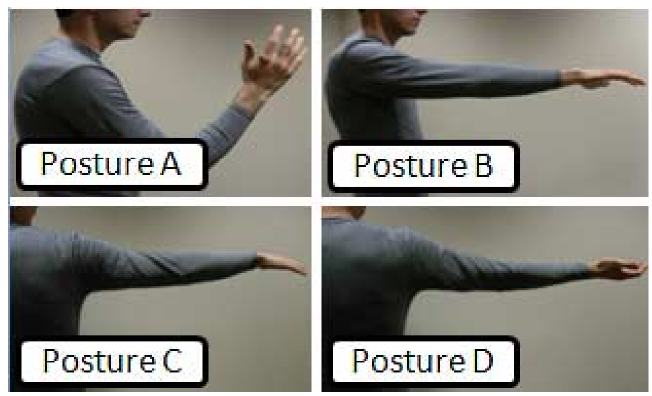

Figure 5. The four novel postures, A, B, C and D, used during the second part of the testing phase.

Figure 5), and assumed to remain the same across different postures, 'Wrist Left' and 'Wrist Right', respectively. This assumption is made throughout the remainder of the paper including results and discussion. Once completing the first pass through the patterns, the vibration patterns were delivered once more. During the training phase, training trials were repeated unless the subject scored a recognition accuracy of at least 80% (7 out of 8 patterns) during a trial. A single training trial involved the random presentation of all eight vibration patterns, once each. Participants were told to respond with the movement the vibration cued, as quickly, but also as accurately, as possible. The experimenter informed the subject about the correctness of each response; if the movement was incorrect, the experimenter demonstrated the correct movement, and presented the pattern once more. During each phase, the experimenter recorded learning rate (training phase only), response correctness and response time. Learning rate is the number of training trials required before the subject passes on to testing. The correctness of each response is used to derive recognition accuracy, or the percentage of correct responses. Response time is the duration between the start time of the presentation of the pattern, and the time at which the subject began performing the correct movement; if incorrect movements were performed first, but then corrected by performing the correct movement, within a time limit of 15 seconds, the response was marked as correct.

The first part of the testing phase was similar to the training phase with the exception that four trials (32 presentations total with four random presentations per pattern) were performed for each subject, and no feedback was given. During the second part of the testing phase, four new postures, depicted in Figure 5, were introduced. The experimenter demonstrated each posture, and explained how the arm should be slightly bent at the elbow while in each posture (not shown in figure) to allow extensions to be performed. Each vibration pattern was presented once for each posture, for a total of 32 presentations. Presentation pairs (*posture*, *vibration pattern*) were randomized. Before each presentation, the participant was informed which posture to change to, after which, the pattern was presented. No feedback was given. Finally, subjects were asked to fill out a questionnaire.

Results: The mean average number of learning trials was 1.9 (SD: 0.99) and 1.4 (SD: 0.7) for "follow me" and push/pull conditions, respectively. Recognition accuracies and classifications for each vibration pattern are summarized in Figure 6. For the "follow me" and push/pull conditions, the overall recognition accuracy for the first part of testing was 97% (SD: 8.8%) and 98% (SD: 6.1%), respectively; and 98% (SD: 8.1%) and 94% (SD: 14.5%) for the second part. Mean response times for each vibration pattern are summarized in Figure 7. For the "follow me" and push/pull conditions, the overall response time for the training phase was 3.6 s (SD: 1.59 s) and 2.8 s (SD: 0.72 s), respectively; for the first part of testing, 2.9 s (SD: 0.96 s) and 2.5 s (SD: 5.9 s); and for the second part of testing, 2.9 s (SD: 0.86 s) and 2.5 s (SD: 0.59 s). Table 1 summarizes results from the post-experiment questionnaire where subjects rated a series of questions using a Likert scale from 1 (low/difficult) to 5 (high/easy). Tables 2 summarizes results pertaining to the subjective naturalness of each vibration pattern, where subjects rated each pattern's naturalness as 'excellent' (perfect or near perfect), 'acceptable' (satisfactory) or 'unacceptable' (needs improvement).

Discussion:

- *Learning Rate:* The average number of learning trials did not differ significantly between conditions, $t(18)=1.30$, $p>0.2$, two-tailed, showing that both conceptual mappings were easy to learn.

- *Recognition Accuracy:* For the first part of testing, the overall recognition accuracy (across subjects) of each vibration pattern (and for either condition) is impressive at 90% or better, with most accuracies being in the high 90's (see Figure 6a). Moreover, a one-way repeated measure ANOVA revealed that recognition accuracies between vibration patterns did not differ significantly, $F(7,63)=1.52$, $p>0.05$, and $F(7,63)=0.93$, $p>0.05$, for the "follow me" and push/pull conditions, respectively. This shows that within each condition, patterns were distinct and easy to recognize. For the second part of testing in which novel postures were introduced, the overall recognition accuracy (across subjects and postures) of each vibration pattern (for either condition) is impressive given no prior training on the novel postures; as depicted in Figure 5b, most accuracies are 90% or better, showing that most patterns, for either condition, were still distinct and easy to recognize even for new postures. However, for the push/pull condition, wrist abduction and adduction were both below 90% at 88% (SD: 13.1%) and 75% (SD: 28.9%), respectively. A two-way repeated measure ANOVA revealed that the main effects for vibration pattern and posture were both significant, $F(7,63)=5.14$, $p<0.0002$, and $F(3,27)=4.33$, $p<0.05$, as well as their interaction, $F(21,189)=3.1$, $p<2\times10^{-5}$. Regarding the main effect of pattern type, Figure 6b suggests lower recognition accuracy for wrist adduction compared to other patterns, regardless of posture. Although we observed slight difficulties with recognizing this pattern while in posture A, B and C, it was posture D that presented the biggest challenge. Regarding the main effect of posture, we observed posture D to have lower overall recognition accuracy, regardless of pattern type, when compared to other postures. However, we observed that the patterns of wrist abduction and adduction created the most problems for participants while in posture D (interaction effect). Overall wrist abduction and adduction accuracy, while in posture D, were both very low at 50% (SD: 52.7%) each. As shown in the confusion matrix of Figure 5b, all five misclassifications of wrist abduction occurred in posture D, whereas half (five out of ten) misclassifications of wrist adduction occurred in posture D; most of the confusion happened between wrist movements. Subjective feedback confirmed the difficultly of recognizing wrist abduction and adduction patterns in posture D for the push/pull condition: many subjects commented that wrist abduction and adduction for push/pull were very difficult to recognize while in posture D due to the (rotated) hand posture. Indeed, in (8) of Table 1, which addresses subjective distinctness and ease of recognition, we see that wrist abduction/adduction were the lowest rated among other patterns in the push/pull condition.

- *Response Time:* After training, overall response times for either condition and for any pattern were impressive, at roughly three seconds or less. Figure 7 shows a general decrease in overall response time (across subjects) for vibration patterns as subjects progressed from training to the first part of testing; then seemingly stabilizing between the first and second part of testing with some small increases or decreases depending on the pattern and condition. A two-way repeated measure ANOVA revealed the main effect of phase type to be significant, $F(2,18)=15.87$, $p<1.1\times10^{-4}$ and $F(2,18)=15.53$, $p<1.21\times10^{-4}$, for "follow me" and push/pull conditions, respectively. Based on Figure 7, this suggests that with continued exposure to the patterns, reaction times improved, with perhaps the exception of the transition between the two parts of testing. This may be due to the introduction of the novel postures, or perhaps more time was needed before we saw further improvements in terms of response time. We hypothesize that over long term use, users will continue to become more proficient at recognizing and responding to the patterns. Only for the "follow me" condition was the main effect of pattern type significant, $F(7,63)=4.13$, $p<8.61\times10^{-4}$. Indeed, from Figure 7, we see that patterns for wrist abduction and adduction were recognized faster on average compared to other patterns. This coincides with subjective feedback: see (8) of Table 1. As expected, this indicates that more natural patterns (see Table 2) will lead to

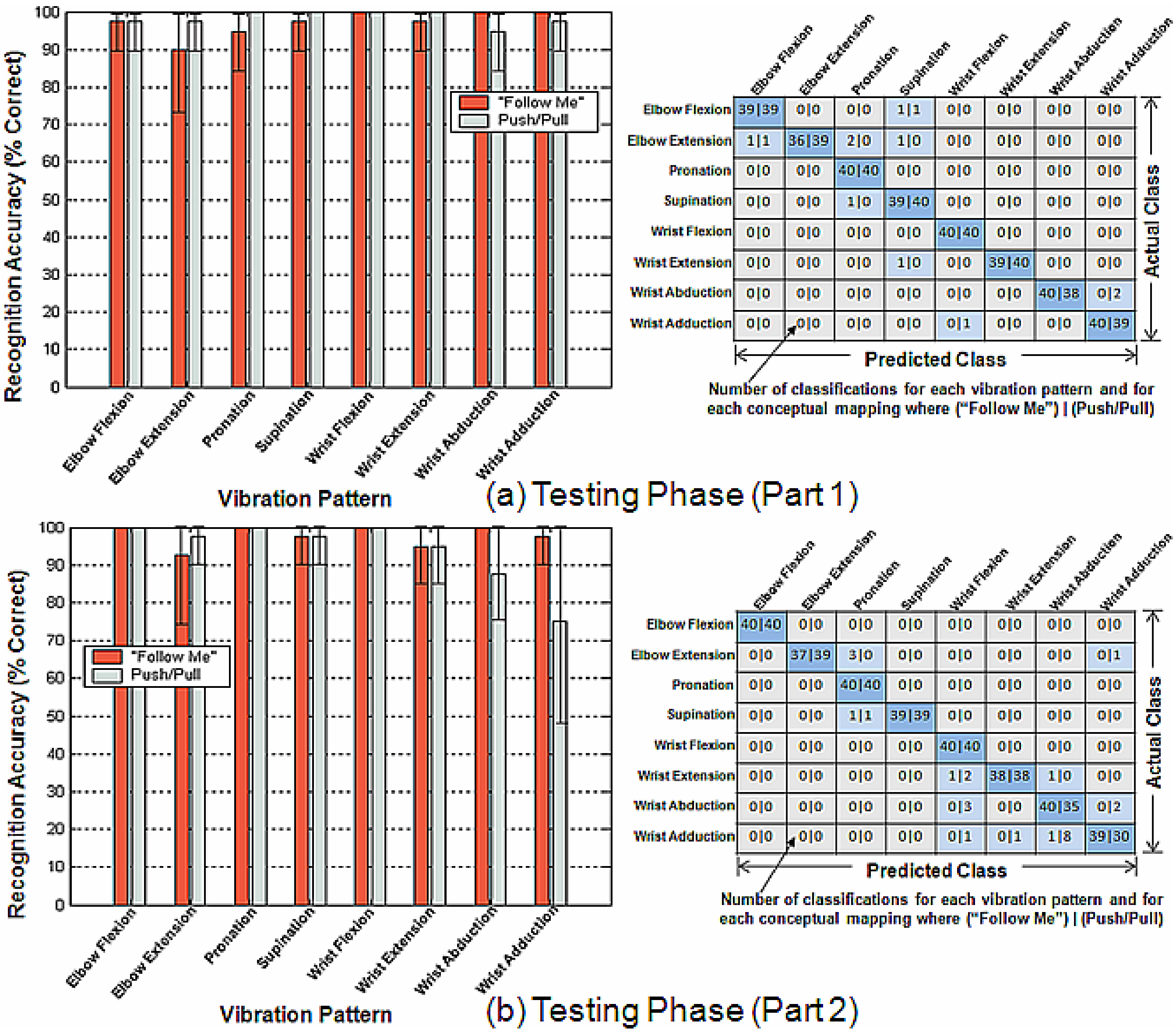

Figure 6. Summary of recognition accuracy for (a) the first part of testing, and (b) the second part of testing. Bar plots (left) show mean recognition accuracies (with standard deviation error bars) for each vibration pattern, averaged across subjects in (a) and averaged across subjects and novel postures in (b). Confusion matrices (right) show the number of times the actual vibration pattern (y-axis) has been classified as the predicted vibration pattern (x-axis), summed across subjects in (a) and summed across subjects and novel postures in (b), where summations are shown using the convention: "follow me" | push/pull. Although rotations appear under the push/pull condition, only the "follow me" concept was used to explain rotations.

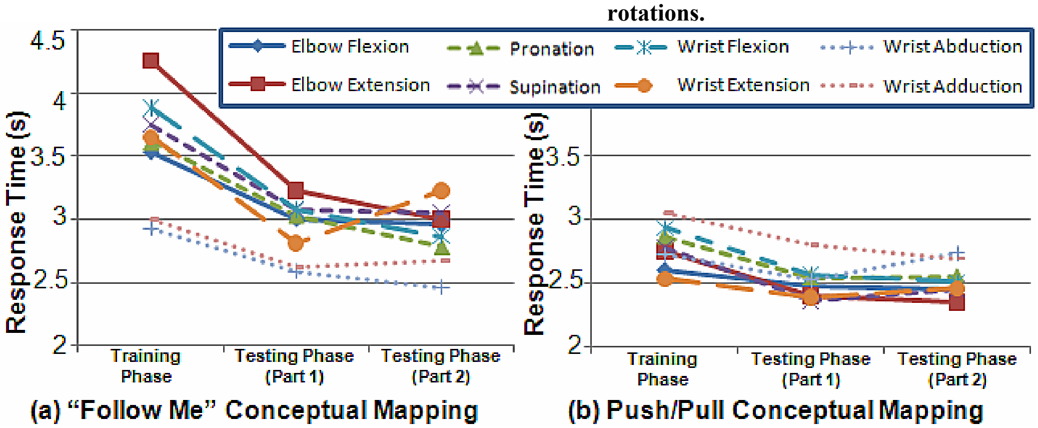

Figure 7. Summary of mean response time for each vibration pattern, averaged across subjects for training and first part of testing, and averaged across subjects and novel postures for second part of testing. Although rotations appear under the push/pull condition, they were always explained using the "follow me" concept.

Table 1. Results of post-experiment questionnaire. Subjects were trained using layman terminology such as 'wrist up' rather than 'wrist extension'. Rotations use the "follow me" concept, even though they also appear in push/pull condition.

Questions	Follow Me		Push/Pull	
	Mean	*SD*	*Mean*	*SD*
1) How easy was it to put on the suit?	3.6	0.42	4	0.67
2) How easy was it to take off the suit?	3.6	0.96	3.7	0.95
3) How easy was it to perform the movements with the suit on?	4.7	0.67	4.9	0.32
4) How comfortable was the suit?	4	0.82	3.9	0.88
5) How lightweight was the suit?	4.9	0.32	5	0
6) How silent were the suit's vibration	4.1	0.57	4.1	0.57
7a) How easy was it to learn the vibration pattern for 'wrist left' (Wrist Adduction)?	4.9	0.32	4	1.25
7b) … for 'wrist right' (Wrist Abduction)?	4.9	0.32	4	1.05
7c) … for 'wrist up' (Wrist Extension)?	4.3	0.67	4.9	0.32
7d) … for 'wrist down' (Wrist Flexion)?	4.4	0.70	4.7	0.48
7e) … for 'rotate right' (Supination)?	4.6	0.69	4.4	1.07
7f) … for 'rotate left' (Pronation)?	4.6	0.69	4.4	1.07
7g) … for 'elbow flex' (Elbow Flexion)?	4.1	0.88	4.9	0.32
7h) … for 'elbow extend' (Elbow Extension)?	4	0.82	4.9	0.32
8a) How easy was it to recognize & respond to vibration for 'wrist left' (Wrist Adduction)?	5	0	3.8	1.03
8b) … for 'wrist right' (Wrist Abduction)?	5	0	4	0.82
8c) … for 'wrist up' (Wrist Extension)?	4.4	0.94	4.7	0.67
8d) … for 'wrist down' (Wrist Flexion)?	4.5	0.96	4.7	0.67
8e) … for 'rotate right' (Supination)?	4.3	0.63	4.3	1.06
8f) … for 'rotate left' (Pronation)?	4.2	0.75	4.3	1.06
8g) … for 'elbow flex' (Elbow Flexion)?	4	0.94	4.8	0.42
8h) … for 'elbow extend' (Elbow Extension)?	3.9	0.99	4.8	0.42

Table 2. Number of votes (out of 10) for each vibration pattern where subjects were asked to vote patterns as 'excellent', 'acceptable' or 'unacceptable' in terms of naturalness. Summations of votes are shown using the convention: "follow me" | push/pull. Rotations use the "follow me" concept, even though they also appear in push/pull condition.

Vibration Patterns	Excellent	Acceptable	Unacceptable
'Wrist Left' (Wrist Adduction)	9|0	1|6	0|4
'Wrist Right' (Wrist Abduction)	9|0	1|8	0|2
'Wrist Up' (Wrist Extension)	2|5	7|5	1|0
'Wrist Down' (Wrist Flexion)	2|4	7|6	1|0
'Rotate Right' (Supination)	6|7	4|2	0|1
'Rotate Left' (Pronation)	6|7	4|2	0|1
'Elbow Flex' (Elbow Flexion)	1|9	8|1	1|0
'Elbow Extend' (Elbow Extension)	1|8	8|1	1|1

- *Posture-Free Vibrations:* With the exception of wrist abduction/adduction for the push/pull condition, based on the impressive recognition accuracies when novel postures were introduced, along with consistent response times, we see that the proposed conceptual mappings and configurations generalize well to new postures that are different from the training posture. This is important as we cannot expect users to re-learn vibration patterns for every new posture they might encounter, which would be unrealistic for many applications. However, we cannot ignore that the vibration pattern for wrist abduction/adduction did not perform well for every posture. We hypothesize that the ideal solution will involve both conceptual mappings, utilizing the most natural patterns.

- *Subjective Feedback:* For the "follow me" condition, vibration patterns for wrist abduction/adduction were rated higher in terms of learnability and distinctness (see Table 1) as well as naturalness (see Table 2) where all but one subject rated the patterns as 'excellent' in terms of naturalness; whereas wrist abduction/adduction for the push/pull condition received no 'excellent' ratings—mostly 'acceptable' or 'unacceptable'. As previously mentioned, subjects felt the latter vibration patterns to be too similar and close to those of wrist flexion/extension. It seems obvious, then, that wrist abductions and adductions should be cued using the "follow me" conceptual mapping with the respective configuration. This will allow for sufficient spacing between wrist flexion and extension vibrations. Wrist flexion/extension under the push/pull condition received higher ratings for learnability and distinctness (Table 1) as well as naturalness (Table 2) compared to the "follow me" condition. Most ratings for the naturalness of wrist flexion/extension, for the "follow me" condition, fell under 'acceptable'; many subjects felt the vibration patterns were more appropriate for rotations, although these patterns were rarely misclassified as such—see Figure 6. The ideal configuration would have motors in a straight line such that the directionality is tangential to the arc of the motion; however, due to the curvature of the skin around the arm, especially around the wrist joint, there is a tradeoff between motor spacing and the curvature of the directionality. Enough spacing is required to provide the illusion of apparent motion, but with larger spacing, motors will cover a greater circumference around the arm. This is an inherent problem when using the "follow me" conceptual mapping to design configurations for flexion and extension, at least where there is limited flatness. Therefore, the conceptual mapping of push/pull seems to be a better option for movements of flexions and extensions. For elbow flexion/extension, there is a clear preference for the push/pull version—see Table 1 and 2. As shown in Table 2, most ratings were 'excellent' whereas most ratings for the "follow me" condition were 'acceptable'. As mentioned, for the "follow me" conceptual mapping, these patterns share the same problem as those for wrist flexion/extension. Indeed, we see that most misclassifications were with rotations—see Figure 6. Lastly, most subjects felt vibration patterns for rotations to be intuitive, easy to learn, and easy to recognize. It is therefore clear that a combination of patterns from the two conceptual mappings explored here is needed rather than using one concept to explain all kinematic-vibrotactile mappings. The most effective patterns from each conceptual mapping should be used: "follow me" wrist abduction/adduction, push/pull wrist flexion/extension, push/pull elbow flexion/extension, and "follow me" rotations.

6. Conclusion and Future Work

This work has proposed a novel kinematic-vibrotactile mapping for instruction-based motor learning, general enough to be used for a variety of applications involving the teaching of motor skills. Two conceptual mappings were explored, and findings indicate that vibration patterns from both mappings should be utilized to ensure learnability and usability. We hypothesize that the nature of the movement (joint/limb articulated, and its type of movement) largely influences how natural a conceptual mapping will be. For example, a vibration running up our arm across our elbow joint seems to be more indicative of flexion compared to a vibration running along the side of our arm near the elbow joint. Indeed, we saw that participants found the former to be more natural (Table 2) and recognized it faster (Figure 7). No experimental comparison with existing approaches has been performed given the difficultly of a direct comparison: our instruction-based approach is unique in that we target low-level, fundamental movements. However, as part of future work, we will perform a study to compare the performance of the proposed approach, for teaching beginners complex movements, with different instruction sets of higher levels of abstraction; the latter of which are commonly used among existing approaches for vibrotactile-based motor instruction. We hypothesize that our approach will be more effective by enabling beginners to gain a foundational understanding of the intricate articulations of complex movements. We are currently extending this approach to accommodate feedback-based motor learning; 6DOF Inertial Measurement Units (IMUs) will be used to measure joint angles and rates of change, and these inputs will drive the spatio-temporal characteristics of vibration patterns proposed here. More specifically, tactile rhythm will convey how to adjust movement speed, and vibrotactile spatial variations will convey how to adjust limb position. By integrating feedback into our instruction set, we will bridge the divide between instruction-based and feedback-based approaches, improving the scalability of the proposed approach by accommodating a greater range of skill level, from beginner to expert. Although simple, low-level movements, i.e., fundamental movements, were assessed here, this was a necessary step to discover distinct and natural vibration patterns that can be used to intuitively build and instruct more complex movements. We plan to conduct several application-oriented user studies to evaluate the aforementioned instruction/feedback based approach for learning complex movements. Specifically, we are targeting motor learning and/or rehabilitation for individuals with sensory, perceptual or physical disabilities. Lastly, we plan to explore how well these conceptual mappings and configurations generalize across the body.

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