Vibrotactile Feedback of Motor Performance Errors for Enhancing Motor Learning

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ABSTRACT
Feedback related to motor performance is integral to improving the control, timing and coordination of movements. However, motor learning traditionally occurs within a group setting, limiting the quality of instruction and feedback. Even during one-on-one instruction, there are impediments to feedback such as physical separation between trainer and trainee, common in many sports such as snowboarding and swimming. We propose an inexpensive solution for real-time vibrotactile positioning and speed feedback that can complement traditional motor learning, and is compatible with existing vibrotactile motor instructions. We present a psychophysical study that examined participants' initial reactions to feedback stimuli pertaining to position and speed adjustments. Results support the proposed design in terms of both usability and naturalness, and provide insight into participants' conceptualization of feedback signals and feedback for rotational movements.

Categories and Subject Descriptors
H.5.2 [User Interfaces]: Haptic I/O.

Keywords
Vibrotactile feedback, instructions, motor learning.

1. INTRODUCTION
Movement is an integral component of perception and action. Through body movement, we not only act upon our environment to alter it, but sense and perceive our surroundings—the percepts of which ultimately influence action. Sensation is mediated through the extensive modalities of our sensory systems. For example, mechanoreceptors of the skin, muscles and joints facilitate rich haptic feature extraction during active exploration of objects and surfaces. We employ manual manipulations to optimize feature extraction through so-called exploratory procedures [1]. Visual sensation and perception requires eye movements (eye saccades) to change the direction of our eye gaze and quick, involuntary, detail-extracting movements between salient visual features while observing a scene.

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We strive to learn new motor skills, and perfect existing capabilities, to enrich our health and well-being through physical activity, recreation, career/job needs, and/or activities of daily living. Given the importance of movement and motor skills, the pedagogy of motor skill acquisition warrants attention.

Traditionally, motor skills are taught within large group classes through observation and mimicry of a trainer's movements complemented with verbal description [2] and visual, auditory and/or physical (contactual) feedback. Effective motor learning requires feedback of motor performance errors. Two types of feedback are available [3]: *intrinsic feedback* naturally occurs as part of actuating and perceiving our own movements; and *extrinsic* (or *augmented*) feedback is provided externally by a trainer or device to complement intrinsic feedback—critical while learning complex, unfamiliar movements. Augmented feedback may describe performance at two levels of abstraction [3]: *knowledge of results* is feedback related to performance goals and achievement of desired movements; and *knowledge of performance* is feedback related to low-level performance attributes such as positioning and speed.

One-on-one (dyadic) instruction provides an ideal setting for motor learning by facilitating high fidelity visual and auditory communication channels with frequent trainer feedback and improved trainee motivation. Given the cost of one-on-one instruction, however, group instruction is more common. But this setting presents several limitations. The difficulty of mimicry, which involves mapping movements onto the trainee's own frame of reference, is amplified when movements must be viewed across a room or from the back of a class. Visual and auditory communication channels become noisy from other students and distractions in the environment. The frequency of feedback is significantly reduced given the divided attention of the trainer as he or she must attend to the entire class. But even one-on-one training has shortcomings. In many sports, for example, there is a large physical separation between the trainer and trainee during motor performances—such as in snowboarding [4]. During this time, trainers cannot provide real-time feedback. For many applications, real-time feedback from the trainer interrupts motor performances, such as while playing a musical instrument, rather than complementing intrinsic feedback in real-time.

Since the 1990's, virtual and augmented reality multimedia systems have been proposed to complement or replace traditional motor learning with real-time visual, acoustic, or kinesthetic motor instruction and/or performance feedback. Virtual reality approaches (e.g., [5]) map a user's physical movements, extracted through visual capture, to a virtual avatar for comparison with a trainer's virtual avatar viewed through a head mounted display.

Acoustic approaches (e.g., [6]) vary dimensions of sound, such as rhythm and tempo, to provide real-time feedback indicative of sensed motor performance characteristics including overall correctness, timing and/or intensity. Kinesthetic approaches (e.g., [7]) provide instruction and feedback through haptic guidance or resistance. However, these approaches tend to be bulky, expensive, lack portability, and/or obstruct modalities (vision, hearing) already occupied as part of the motor learning task.

An alternative channel for communicating performance errors is vibrotactile stimulation of the skin. This form of communication provides a solution that is inexpensive, wearable, portable, unobtrusive and discreet. Section 2 presents related work and proposed approaches for vibrotactile instruction or feedback. In section 3, we present a novel vibrotactile feedback system which addresses the limitations of current approaches. Section 4 gives the details of the implementation. In section 5, two psychophysical studies are presented that assess the naturalness and usability of our proposed approach. Finally, in section 6, possible directions for future work are outlined.

2. RELATED WORK

Lieberman and Breazeal's Tactile Interaction for Kinesthetic Learning (TIKL) system [8] complemented traditional motor learning and physical therapy with vibrotactile feedback delivered to the arm. Trainees watched a video of a movement being performed, and then attempted to mimic the movement. The location of the vibrotactile stimulation on the arm indicated the joint position in error (with respect to a fundamental movement), and the intensity of the vibration was proportional to the degree of error. Errors are corrected by moving in the opposite direction of the vibration; that is, the stimulation "pushes" the limb it stimulates. Saltation patterns, rather than localized stimulation, were used as feedback for forearm rotations. Saltation [9] is a perceptual illusion that gives the impression of phantom vibrotactile bursts traveling across the skin between actual stimulated sites.

Spelmezan et al. [4] proposed *tactile motion instructions* for snowboarding. Saltation patterns traveling the length of the legs or torso, or around the torso, could be actuated by a coach as an instruction or feedback to flex/stretch the legs; shift weight left/right or front/back; or rotate the upper body, respectively. The directionality of the saltation patterns were interpreted as "pushing" or "pulling"; Spelmezan et al. referred to this conceptual mapping as the *push* or *pull metaphor*.

McDaniel et al. [10] proposed vibrotactile motor instructions for targeting fundamental movements of the arm for use in any motor learning application. Saltation patterns were used given their intuitiveness for conveying directionality. Two conceptual mappings were explored: *push/pull metaphor* and the *follow-me concept*, each with different motor configurations.

The StrokeSleeve [11], intended for rehabilitation, is a wearable sleeve augmented with vibrotactile actuators for real-time joint angle error feedback, and magnetic trackers for motion capture. A band of vibration motors near the wrist joint was used for elbow flexion/extension and shoulder rotation feedback; and a band near the elbow joint was used for shoulder flexion/extension and shoulder abduction/adduction feedback. Vibrations were interpreted as "attracting" ("pulling") a limb.

Wall, III and Kentala [12] developed a waist-worn device for vibrotactile feedback of body tilt to help vestibulopathic patients control their balance and reduce sway. Vibration motors were arranged on the stomach (just above the waist) and back (just above the waist) each in two columns of three vibration motors each to convey forward tilt and backward tilt, respectively. As tilt increases, vibration motors farther from the waist (i.e., higher up the columns) were actuated. An inertial measure unit was used for tilt measurements.

Existing approaches for vibrotactile instruction and feedback have several limitations. The aforementioned approaches are largely designed to deliver either instruction or feedback, but not both. Some instruction-based approaches, such as [4][10], may be used to provide feedback (e.g., if the wrong movement is performed, the correct movement may be presented), but only at a high-level without capabilities for motion guidance. Currently, vibrotactile feedback systems, such as [8][11], deliver instructions through video media, which increases costs, reduces portability and limits applicability to those applications where the visual modality is available for communication. Therefore, a novel vibrotactile instruction/feedback design is needed to improve versatility, ensuring applicability to a multitude of motor learning applications and scenarios including those where the visual and/or auditory modality are unavailable or overloaded.

Thus far, vibrotactile feedback approaches have focused on performance errors related to joint angles, largely ignoring joint angle rate. Joint angle rate (or speed) is an important characteristic of movement related to timing, intensity, control and coordination. No vibrotactile feedback designs, with the exception of the TactaPack, present speed error information for speed adjustments. The TactaPack [13], developed by Lindeman et al., provides vibrotactile feedback ("nudges") during physical therapy activities to alert the user when a target acceleration is exceeded or not yet reach. No vibrotactile design details are given, and the proposed approach is more of a conceptualization or proof-of-concept with no usability study conducted to evaluate naturalness and usability of the signals. Lastly, in addition to tilt angle, Wall, III and Kentala [12] explored the presentation of tilt rate, but to adjust tilt rather than tilt speed.

Finally, although proposed vibrotactile feedback systems have been evaluated through studies involving complex movements consisting of multiple fundamental movements [8][11], no psychophysical analysis of *individual signals* has been conducted to assess distinctness and naturalness through initial reactions and response time. Such data is the foundation for developing more complex motor learning systems across different applications domains.

To fill these gaps, we propose a wearable device for vibrotactile feedback that provides the following contributions over existing approaches: (1) Two modes of feedback: positioning (joint angle) error and speed (joint angle rate) error for position and speed adjustments, respectively; (2) A vibrotactile feedback design that is compatible with and facilitates vibrotactile motor instructions for improved applicability and usability by avoiding potentially unavailable or overloaded modalities (namely, vision or hearing); and (3) A psychophysical evaluation to gauge initial reactions and response times of these stimulations to better understand the intuitiveness and usability of feedback information delivered to the skin. Moreover, the proposed system is designed for portability and affordability ($500 or less) through use of inertial measurement units for motion capture and wearable electronics powered by rechargeable batteries. Fundamental movements are targeted, rather than application-specific movements, to keep the system versatile in that it may be used across many motor learning application domains such as sports training, music and rehabilitation. Integrating vibrotactile instructions and feedback will support training regimens created by coaches, therapists and other movement instructors. Vibrotactile feedback can provide discreet, real-time error information during a motor performance (e.g., playing a sport) that may lessen distraction compared to other modalities such as vision or hearing. Lastly, the portability offered by the proposed approach is critical in many applications such as sports and tele-rehabilitation.

3. APPROACH

Two types of feedback related to performance errors are explored: (1) positioning errors with respect to joint angle or degree of rotation; and (2) speed errors with respect to joint angle rate or rotation rate. For versatility, we target fundamental movements as almost any complex movement may by decomposed into a sequence of fundamental movements. The human body's most basic movements consist of five fundamental movements [14]: flexion, extension, abduction, adduction and rotation. Assume the body to be in the anatomical position with arms extended by the side and palms facing forward. For movements occurring within the sagittal plane (which divides the body through its midline), flexion/extension decreases/increases the joint angle. For movements occurring within the frontal plane (which divides body into front and back), abduction/adduction is movement away/toward the sagittal plane. For movement occurring within the horizontal plane (which divides the body into a top and bottom), supination/pronation is rotation away/toward the sagittal plane. These five fundamental movements are found across the body, articulated by rotary joints and uniaxial, biaxial and triaxial hinge joints. To simplify both the proposed implementation and user study, we limit the focus to fundamental movements of the right arm below the shoulder.

To ensure that the proposed vibrotactile feedback design is compatible with vibrotactile instructions, we chose an existing, versatile, well-documented vibrotactile instruction set to base our design upon: vibrotactile motor instructions [10]. As previously described, these instructions use saltation patterns, and although different conceptual mappings were explored [10], those found most natural by participants were chosen:

- Elbow joint flexion and extension are cued with vibrotactile stimulations traveling up or down, respectively, the length of the arm, centered at the elbow joint (ventral side). This conceptual mapping is referred to as the *push/pull metaphor* since the directionality of the vibration simulates "pushing" or "pulling" of the forearm.
- Forearm supination and pronation are cued with vibrotactile stimulations traveling clockwise or counter clockwise, respectively, through a cross-section of the forearm (roughly centered between the wrist and elbow joint). Rotations use the conceptual mapping, *follow-me*, since it is intuitive to rotate along the direction of stimulation.
- Wrist flexion and extension are cued with vibrotactile stimulations running medially along the wrist from the dorsal to ventral side, or ventral to dorsal side, respectively. The *follow-me* concept is used given the naturalness of following the vibrations "up" or "down". To accommodate motion sensors, these vibration motors were moved onto the hand, just anterior to the wrist joint.
- Wrist abduction and adduction are cued with vibrotactile stimulations running medial to lateral, or lateral to medial, respectively, across the back of the hand. The *follow-me concept* is used given the naturalness of following the vibrations "left" or "right". These vibration motors were moved distally onto the fingers to accommodate motion sensors.

The proposed feedback designs, described next, utilized the aforementioned motor configurations for seamless integration between instruction and feedback. The relative angles between limbs are extracted in real-time through use of on-body inertial measurement units, described in Section 4.

3.1 Feedback for Positioning Errors

The feedback signal for positioning errors is inspired by the gentle nudges delivered by a physical therapist for guiding movements; it is in the form of quick, gentle vibrotactile bursts of duration 120 ms (separated by gaps of 120 ms). Pilot tests revealed this "tapping" signal to feel natural for guiding a limb to a correct position. A steady, constant vibration was also evaluated, and found to be just as natural. The choice between these feedback signal designs will ultimately depend on the application and preference of the user. When a user reaches a target angle, the vibration stops (plus or minus an acceptable amount of error—referred to here as *padding*). Pilot tests revealed that insufficient padding frustrated users. Therefore, a padding of at least +/- 5 degrees (or more) is recommended for usability; but the amount of padding will ultimately depend on the application. Lastly, the steady vibration, as opposed to the tapping vibration, may be more applicable for those applications requiring accurate positioning with small errors given timing delays (120 ms or less) introduced by the pauses between taps.

The motor configuration and positioning feedback signal design for each fundamental movement is depicted in figure 1. The design utilizes the motor configurations of the instructions previously described to facilitate the seamless delivery of feedback following the presentation of an instruction. For scalability, the system provides the option of using feedback separate from instructions, which might be more applicable to expert users who are perfecting known movements; as opposed to novice users who benefit from knowing what movements to perform, perhaps as part of a trainer's recommended practice regimen, followed by feedback to improve the movements. The general operation of positioning feedback mode, irrespective of joint, is now described; followed by joint-specific vibrotactile stimulation.

Upon receiving a vibrotactile instruction, e.g., flex or extend at the elbow joint, the user performs the requested movement, attempting to reach a target angle (potentially unknown on the first attempt). When the user stops moving, if his or her joint angle is not within the padding of the target angle, vibrotactile feedback will guide the limb to the correct angle (if the user instead reached the correct angle, no feedback would be felt). Vibrotactile stimulation ceases when the correct angle is reached.

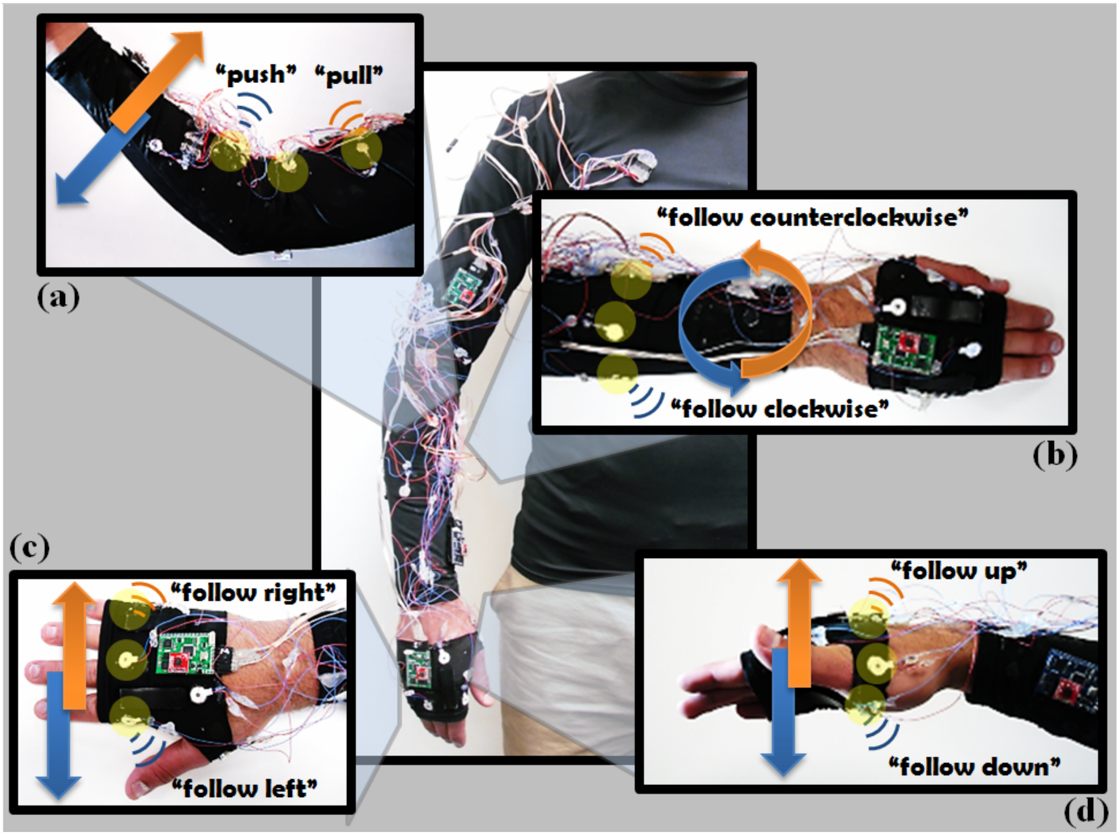


Figure 1. Motor configurations (highlighted in yellow) for delivery of both instructions and positioning feedback for each fundamental movement of the right arm: (a) flexion/extension at elbow joint; (b) supination/pronation of forearm; (c) abduction/adduction at wrist joint; and (d) flexion/extension at wrist joint. The postures shown are those used during the user study (section 5). Abduction/adduction is specific to the posture shown. The “pulses” indicate the motors used as part of feedback, and the arrows indicate the intended direction of movement based on the feedback signal.

To ensure the user has found the correct position, the system requires the user to hold the position for a short duration (less than a second) before providing a stimulation (a vibration running up the length of the arm) to indicate correctness.

Positioning feedback for elbow flexion/extension (figure 1a) taps the ventral side of the forearm to “push” the forearm to extend the limb at the elbow joint; and taps the ventral side of the upper arm (above the area of the bicep) to “pull” the forearm to flex the limb at the elbow joint. The angle of elbow flexion/extension is determined by the relative angle between the forearm and upper arm. Positioning feedback for rotation (figure 1b) taps the lateral side of the forearm to cue a clockwise rotation (supination); or taps the medial side of the forearm to cue a counterclockwise rotation (pronation). The degree of rotation is determined by the orientation of the hand relative to the upper arm. Positioning feedback for wrist abduction/adduction (figure 1c) taps the lateral side of the hand on the little finger to cue abduction; and taps the medial side of the hand on the index finger to cue adduction. The angle of wrist abduction/adduction is determined by the relative angle between the hand and forearm. Positioning feedback for wrist flexion/extension (figure 1d) taps the volar side of the hand to cue a flexion at the wrist joint; and taps the dorsal side of the hand to cue an extension at the wrist joint. The angle of wrist flexion/extension is determined by the relative angle between the hand and forearm.

The aforementioned design was extensively evaluated through pilot testing. Participants found both the vibration signal and interactivity of the system natural for correcting positioning errors. Regarding interactivity, participants appreciated the mirrored feedback resulting from overshooting and undershooting a target angle. This allowed users to get a “feel” for the correct position on the first attempt, after which they could accurately move to the correct angle on subsequent tries, usually without needing guidance even when small padding was used. The system delivers feedback for only one fundamental movement at a time since, especially for novices, too much feedback can overwhelm and distract students—feedback related to a specific error, preferably the movement most in error, is more useful for effective motor learning [3].

3.2 Feedback for Speed Errors

The feedback signal for speed errors indicates the direction to adjust speed (slow down or speed up) through tempo variations of a vibrotactile rhythm. The rhythm is presented to the elbow for a common body site across all arm movements, and to ensure distinctness from vibrotactile instructions and other feedback signals. Two presentation modes were evaluated through pilot testing: real-time speed feedback and near real-time speed feedback.

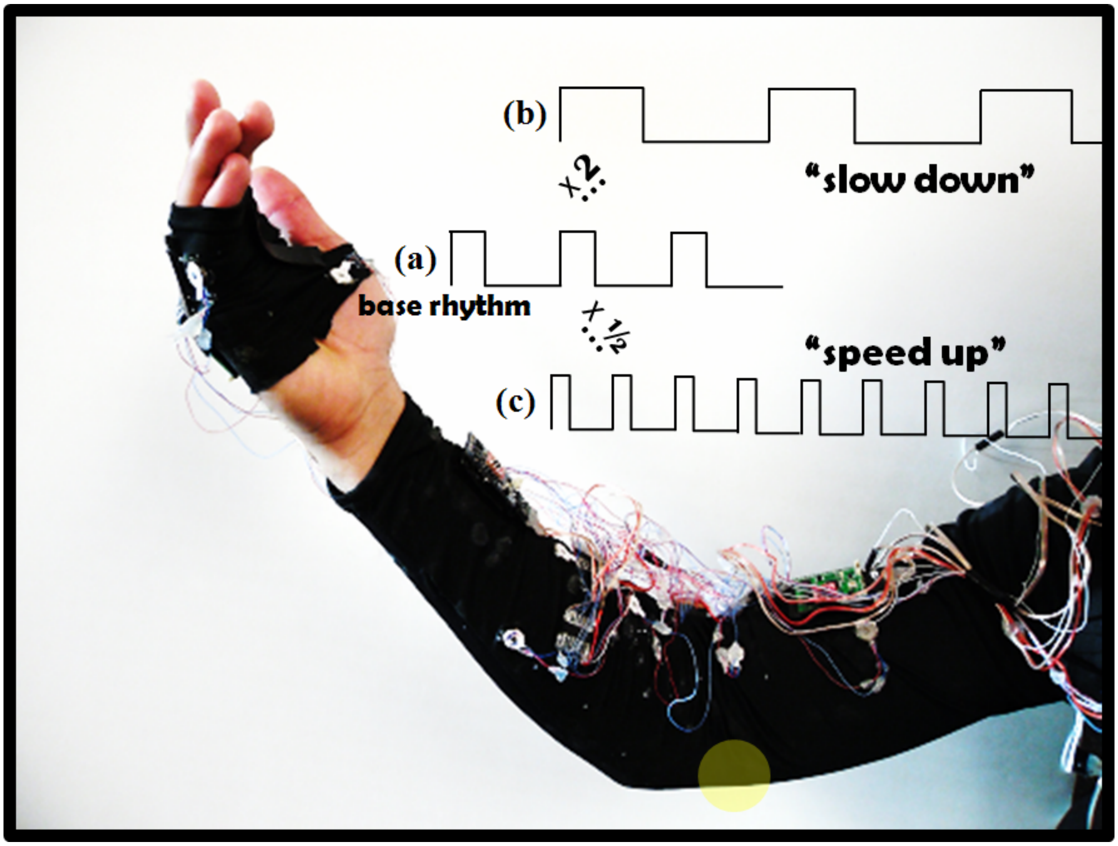


Figure 2. Visualization of vibrotactile rhythms for correcting speed errors. Rhythms are presented near the elbow (highlighted). The rhythms for slowing down or speeding up both begin with a base rhythm (a), followed by either a tempo decrease (b) or tempo increase (c), respectively. The base rhythm consists of three pulses, each of 200 ms duration, separated by 500 ms, for a total duration of 2.1 seconds at 1.428 pulses/s. The tempo decrease consists of three pulses, each of 400 ms duration, separated by 1000 ms, for a total duration of 4.2 seconds at 0.714 pulses/s. The tempo increase consists of nine pulses, each of 100 ms duration, separated by 250 ms, for a total duration of 3.15 seconds at 2.857 pulses/s.

For real-time speed feedback, a slow rhythm tempo indicates "slow down" and a fast rhythm tempo indicates "speed up", presented in real-time during a movement, and dependent upon the user's current speed. The rhythm ceases when the target speed is reached (within a pre-defined padding) and maintained. This mode of speed feedback was not successful during pilot testing. The tempo fluctuated too rapidly due to acceleration at the start of a movement, deceleration toward the end of a movement, and not enough time to respond to the feedback given the short range of motion involved in most fundamental arm movements.

Further pilot testing revealed a near real-time feedback scheme to be a more useful and natural form of speed feedback where speed adjustment is presented after a movement based on the median speed to remove acceleration/deceleration effects. After a user feels a vibrotactile motor instruction, he or she performs the requested fundamental movement with a constant speed. After stopping, if the speed is not within the padding of a target speed, or a pre-defined speed range (e.g., "slow", "medium", etc.), the speed adjustment is presented to the user's elbow (figure 2). A base rhythm (figure 2a) is presented, followed by a tempo change: a tempo decrease indicates "slow down" (figure 2b), whereas a tempo increase indicates "speed up" (figure 2c). Pilot test participants found the tempo variations intuitive, and easy to learn and recognize. After the rhythm is presented, users move with an updated speed, and the system once again compares the user's speed with the target speed. This procedure repeats until the target speed is reached, which then initiates a vibration running up the length of the arm to indicate correctness. As before, pilot test participants appreciated the interactivity of the system. They also appreciated that the rhythm was always presented to the same body site rather than localized for each joint.

4. IMPLEMENTATION

Inertial measurement units (IMUs) were used for motion capture to enhance portability and affordability compared to other motion capture solutions such as magnetic tracking or marker-based visual capture. Although more accurate (but more expensive) sensing platforms exist, the accuracy of IMUs is sufficient for motion sensing where individual IMU measurements for roll, pitch and yaw were found to be accurate up to several degrees relative to Earth when drift errors are handled appropriately. An IMU uses an accelerometer and gyroscope to sense acceleration and angular velocity, respectively—the data of which is sufficient for computing the relative orientation between IMUs. We used the ArduIMU+ V2 (Flat), which has a triple-axis accelerometer, triple-axis gyroscope and onboard processor. A triple-axis magnetometer was later added to account for drift errors. The

Attitude Heading Reference System (AHRS) firmware was used for calculating roll (around the sensor's x-axis), pitch (around the sensor's y-axis) and yaw (around the sensor's z-axis). Each IMU was calibrated once, and the calibration file was loaded automatically for subsequent start-ups. The roll, pitch and yaw samples of each IMU are sent to a LilyPad microcontroller (ATmega328). The microcontroller also controls vibration motors (pancake motors, 150 Hz). All electronics are attached to a Men's compression shirt; vibration motors and IMUs are attached to the sleeve (figure 1), whereas the microcontroller and power supply are attached to the back of the shirt. The construction of a custom actuator/sensor sleeve (as described) was decided over leveraging an existing technology, such as smartphones, due to size and weight restrictions. While smartphones have impressive computational power, vibrotactile feedback capabilities and a multitude of motion sensors, they are and will remain too bulky to attach to most parts of the body; e.g., the back of the hand. Furthermore, we attach many actuators embedded in a bodysuit.

The back of the hand, the medial side of the forearm, and the area above the bicep of the upper arm, were each augmented with an IMU via Velcro (figure 1)—which we refer to as *IMU_H*, *IMU_F* and *IMU_B*, respectively. We refer to the *forward-vector*, *side-vector* and *up-vector* as those vectors aligned with the sensor's local coordinate system (x, y and z), which rotates through space as the orientation of the sensor changes. To calculate joint angles, we compared the orientation between IMUs within a specific plane. The angle between *IMU_F*'s *forward-vector* and *IMU_B*'s *forward-vector* gives the angle between the forearm and upper arm related to elbow flexion/extension. The angle between *IMU_H*'s *up-vector* and *IMU_F*'s *forward-vector* gives the angle between the hand and forearm related to wrist flexion/extension. The angle between *IMU_H*'s *side-vector* and *IMU_F*'s *forward-vector* gives the angle between the hand and forearm related to wrist abduction/adduction. The angle between *IMU_H*'s *side-vector* and *IMU_B*'s *side-vector* gives the degree of rotation between the forearm and upper arm related to forearm supination/pronation.

The *forward-vector*, *side-vector* or *up-vector* of an IMU was found by rotating the respective unit vector (along x, y or z) using the following rotation matrices:

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & -\sin(roll) \\ 0 & \sin(roll) & \cos(roll) \end{bmatrix},$$

$$R_y = \begin{bmatrix} \cos(pitch) & 0 & \sin(pitch) \\ 0 & 1 & 0 \\ -\sin(pitch) & 0 & \cos(pitch) \end{bmatrix},$$

$$R_z = \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

where *roll*, *pitch* and *yaw* are the sensor's current orientation estimates in radians. The angle theta between any of the aforementioned vectors was calculated by rearranging the dot product:

$$\theta = \cos^{-1}\left(\frac{\boldsymbol{a} \cdot \boldsymbol{b}}{\|\boldsymbol{a}\|\|\boldsymbol{b}\|}\right)$$

where $\boldsymbol{a}$ and $\boldsymbol{b}$ are vectors.

Each IMU is sampled at 8 samples/s. This sampling rate was largely determined by the overhead of the LilyPad's firmware—particularly, the processing requirements to actuate vibration motors and sense the IMUs simultaneously during feedback mode. However, this sampling rate was found to be sufficient for the slow to moderate speed movements involved; fast movements were not tested as these saturated the gyroscopes of the IMUs.

Feedback for either positioning errors or speed errors begins after a user has started and stopped a movement. We refer to this movement as the initial movement. A threshold speed is used to discard false movements such as jitter. A movement is considered the initial movement if it has a speed of 15˚/s or greater, and maintains this speed for at least 3 samples—after which, falling below 15˚/s will initiate feedback. Pilot testing revealed the aforementioned threshold speed to work well in terms of ignoring subtle, unintentional movements and jitter.

A graphical interface was developed to provide control over system operation. Through the user interface, users can send vibrotactile motor instructions; record movements without feedback; record movements with positioning feedback by entering a fundamental movement and target angle (with padding); record movements with speed feedback by entering a fundamental movement and target speed (with padding). The user interface also has parsing capabilities in that users can segment raw motion data files into fundamental movements based on speed thresholds (such as 15˚/s).

5. USER STUDY

Aim: A user study was conducted to assess the distinctness, naturalness and usability of the proposed feedback designs, respectively position and speed adjustments, through two experiments. Each subject participated in both experiments (within-subject design), and the order of experiments was counterbalanced to remove order effects. The study was approved by Arizona State University's Institutional Review Board.

Subjects: Sixteen subjects (8 males, 8 females) completed the study. Ages ranged between 18 and 32 (*M:* 24, *SD:* 8). No subjects had any known motor or tactile impairments.

Apparatus: The firmware and software of the system was altered to accommodate the study. In particular, feedback was not linked to motor performance—that is, requiring a user to reach a desired target angle or speed; but rather, feedback signals were randomly presented, and initial responses were recorded, for psychophysical assessment of initial reactions to the stimuli. The raw movement recordings were automatically annotated with the start and end angle and timestamp of the initial movement, and the time in the recording when feedback began. Samples were recorded every 120 ms. A motion segmentation algorithm accommodated slow speeds captured during feedback. A speed threshold of 5˚/s was used to segment responses to positioning feedback as well as speed feedback instructing to slow down since participants often responded with very slow speeds. A speed threshold of 15˚/s was used to segment responses to speed feedback instructing to speed up since faster speed responses were made. All slow movements were manually verified as valid movements as opposed to jitter based on their timing and range of motion.

Procedure: Each participant was randomly assigned in advance the order in which the experiments were applied. After donning the wearable system, participants were introduced to layman terminology for describing the movements involved: *elbow-*

up/elbow-down (elbow flexion/extension, arm held out in front of body with palm facing up); *wrist-up/wrist-down* (wrist extension/ flexion, arm held out in front of body with palm down), *wrist-right/wrist-left* (wrist abduction/adduction, arm held out in front of body with palm down), *rotate-clockwise/rotate-counterclockwise* (forearm supination/ pronation, arm held out in front of body). During this time, the experimenter demonstrated these movements. Participants were asked to stand facing the experimenter during the study, but were allowed to sit during breaks which could be taken as often as needed.

In both experiments, participants underwent a familiarization, training and testing phase each involving recording sessions where movements are recorded during feedback presentation. A recording session is referred to as a *trial*. As the focus of this evaluation is on feedback rather than instruction, before each trial, the participant is instructed by the experimenter (rather than the system) to perform a specific *initial* movement before feedback is felt. For example, during testing, participants are instructed to perform an *elbow-up*, *elbow-down*, etc. before feedback is felt. During familiarization and training, the direction of the initial movement is not controlled—for example, the experimenter would inform the participant to perform an elbow movement, either up or down. The initial movement direction was counterbalanced across testing trials to reduce effects of movement direction immediately before feedback is felt. Since the IMUs' gyroscopes saturate at high speeds, participants were asked to perform smooth, constant speeds at slow (15˚/s) to moderate (100˚/s) speeds during the study. These speeds were demonstrated to subjects by the experimenter. The following description of the different phases of the study is the same for both experiments.

During familiarization, participants were introduced to the purpose and operation of the system, and presented with all eight feedback signals. We refer to the presentation of all eight feedback signals as a *set*. Repetitions were allowed, and participants were told in advance the adjustments that the feedback signals would request.

During training, a sequence of sets was presented to participants. Within each set, the order of feedback signals is randomized. The experimenter corrected wrong guesses (adjustments), and confirmed those that were correct. To move onto testing, participants had to achieve a recognition accuracy of 80% or better (7 out of 8 feedback signals). Since analysis is done offline through a parsing algorithm, the experimenter provided feedback manually through visual observation (training phase only). Responses were documented as *correct*, *incorrect* or *corrected*, where the latter response involves an incorrect initial reaction followed by an adjustment to correct the response. Corrected responses are found only for positioning feedback since speed feedback is near real-time. Those corrected responses with excessive durations (> 500 ms) were not counted in favor of the 80% threshold. Observational accuracy was later confirmed through performance comparison with parser.

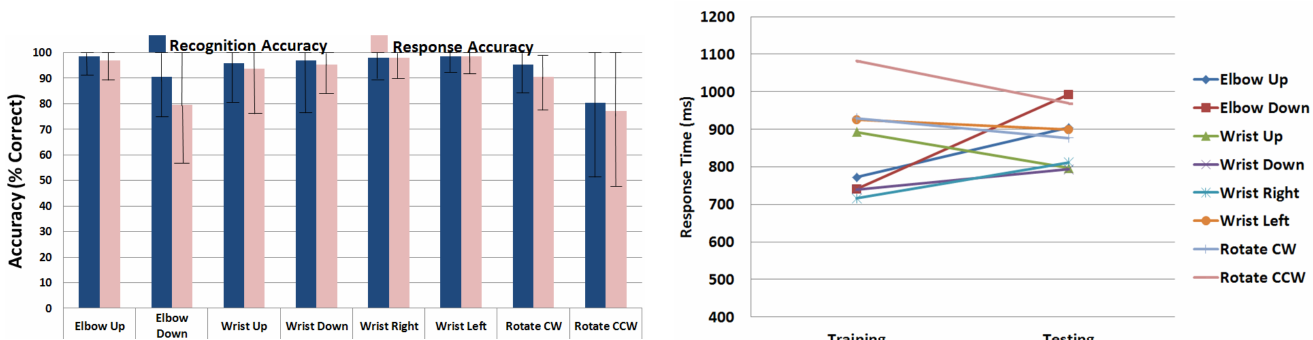
During testing, each of the eight feedback signals were presented four times (initial movement directions were counterbalanced) with their order randomized for 32 trials in total. The experimenter did not provide feedback during testing. After the completed user study, participants were asked to fill out a questionnaire pertaining to the usability of the system, and the distinctness, naturalness and usability of the feedback signals.

Regardless of phase, each trial involved the following system operation (positioning feedback is described first, following by speed feedback): A trial begins with the participant feeling a one second vibration, "start signal", at the dorsal side of the elbow joint. Participants are asked to move only after the start signal ends as this is when the system begins recording. As previously described, the system detects a movement when 15˚/s is surpassed and briefly maintained. (During familiarization, participants are asked to move faster when speeds are too slow for system detection.) Since participants will need to adjust their position once the initial movement is completed, they are asked to stop in the center of their full range of motion of the involved joint. Once the initial movement is completed, the system immediately delivers feedback to adjust position (left or right, up or down, clockwise or counterclockwise, depending on the fundamental movement). The participant follows the feedback to adjust his or her current position until the experimenter stops the recording. For this study, feedback is not linked to motor performance (no target angle or target speed is needed for each trial).

The operation of the system during near real-time speed feedback is slightly different from that of real-time positioning feedback: As before, a trial begins with the participant feeling a start signal—this time, at the back of the hand to avoid confusion with the rhythms presented to the elbow joint. Participants were once again asked to move only after the "start signal" ends, and a speed threshold of 15˚/s is also used for this experiment. After stopping (participants were instructed to move through their full range of motion), participants immediately feel a feedback signal at their elbow requesting a speed adjustment (slow down or speed up). While the rhythm is being presented, the system does not record movement. During this time, the participant moves back to his or her starting position, and waits briefly for the second "start signal"; after which, the participant moves through his or her full range motion with the updated speed based on the feedback. Recording commences immediately following the second start signal. As before, feedback signals are randomly presented by the experimenter as opposed to being linked to actual motor performance (for the purposes of this psychophysical analysis).

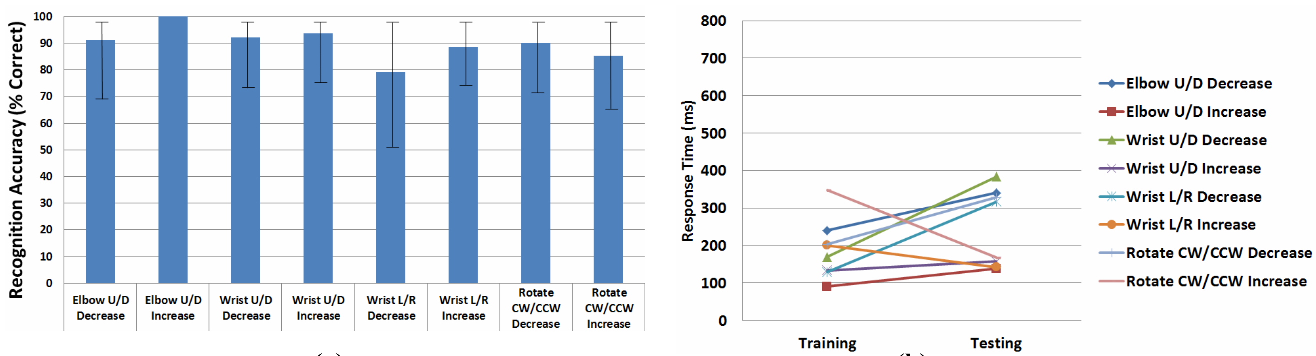
Results: The mean number of training sets for each experiment was 1.25, *SD:* 0.57 (positioning feedback) and 1.12, *SD:* 0.34 (speed feedback). For positioning and speed feedback, 160 and 144 training trials were captured, respectively. The data files from 7 and 12 trials, respectively, were corrupted due to sensor saturation and were omitted from the analysis. Coherence between experimenter feedback during training and the segmentation algorithm was later verified; no inconsistencies were found for positioning feedback, and only four inconsistencies (out of 144 trials) were found for speed feedback during training.

For responses to positioning feedback, we differentiate between what we term *recognition accuracy* and *response accuracy*. We define recognition accuracy as the number of both correct and *corrected* responses out of the total number of trials, where a corrected response is initially incorrect, but eventually corrected. Response accuracy does not count corrected responses as correct, and therefore considers only the initial reaction to the stimuli. The mean recognition and response accuracy for positioning feedback, averaged across participants and signals, was respectively, 94.2%, *SD:* 6.2% and 91.2%, *SD:* 7.1%. Mean recognition and response accuracies for individual signals are shown in figure 3(a). Only 14 testing trails involved corrected responses; and of these, nine



(a) **(b)**

Figure 3. Positioning feedback results: (a) Mean recognition accuracy and response accuracy per signal. Error bars are standard deviations. (b) Mean response time per signal between training and testing.



(a) **(b)**

Figure 4. Speed feedback results: (a) Mean recognition accuracy per signal. Error bars are standard deviations. (b) Mean response time per signal between training and testing.

responses were corrected in less than a second, three in just over a second; and two in about two seconds. Of the 512 recorded testing trials, 18 were corrupted due to saturation; these were omitted from analysis. For speed feedback, we do not differentiate between recognition and response accuracy since the user performs one speed adjustment movement, which is recorded as correct or incorrect. The mean recognition accuracy for speed feedback, averaged across participants and signals, was 90%, *SD:* 9.7%. Mean recognition accuracies for individual signals are shown in figure 4(a). As before, some recorded testing trials were corrupted due to saturation; 20 trials out of 512 were corrupted, and hence, omitted from analysis.

Response time to stimuli was extracted from the files of recorded trial data. For positioning feedback, response time is defined as the time between onset of the feedback signal, and movement in response to this signal. For speed feedback, response time is defined as the time between the end of the second start signal, and movement in response to this event. The mean response time for positioning feedback, averaged across participants and signals, was 847 ms, *SD:* 202 ms, and 881 ms, *SD:* 205 ms, for training and testing respectively. The mean response time for speed feedback, averaged across participants and signals, was 198 ms, *SD:* 214 ms, and 247 ms, *SD:* 182 ms, for training and testing respectively. Mean response time for individual signals during training and testing are shown in figure 3(b) and 4(b) for positioning feedback and speed feedback, respectively. Lastly, mean responses to general usability questions are shown in table 1; and mean responses to questions related to the learnability, distinctness and naturalness of positioning and speed feedback signals are shown in table 2 and 3, respectively.

Discussion: The learning rate of both experiments, estimated in terms of the mean number of training sets, is impressive, showing that the feedback signals were easy to learn. This correlates with subjective results where participants gave high marks to learnability: table 2, *Q2*, and table 3, *Q2*, for positioning and speed feedback, respectively. Given these short training times, the mean recognition and response accuracies for positioning feedback, figure 3(a), are impressive. However, a significant difference was found between recognition accuracies, $\chi^2(7) = 20$, $p < 0.05$, and response accuracies, $\chi^2(7) = 18.2$, $p < 0.05$, indicating that some feedback signals were more difficult to recognize than others. Indeed, the recognition and response accuracies for 'Elbow Down', 'Rotate CW' and 'Rotate CCW' are noticeably lower, although still satisfactory, compared to other signals. These results correlate with subjective feedback in terms of both ease of recognition (table 2, *Q1*) and naturalness (table 2, *Q3*). Half of participants commented that is was difficult to adjust to the "pushing" involved in 'Elbow Down' as all other movements used the *follow-me concept*. Under the *push/pull metaphor*, participants were trained to interpret a vibration on the ventral side of the forearm as "pushing". However, if participants were expecting a *follow-me* signal, then this same stimulation would be interpreted as "pulling". Indeed, 9 of the 14 corrected movements were corrections for misinterpreting 'Elbow Down' as 'Elbow Up'. The signal for 'Elbow Up' was confused less often given that a *follow-me signal* would occur on the dorsal side of the forearm rather than above the area of the bicep. This confusion seems to indicate difficulty with switching between conceptual mappings, at least with the limited training underwent by participants during this study. Therefore, to reduce training and improve usability, it is recommended that a consistent conceptual mapping is used across all positioning feedback signals. Six participants commented that positioning feedback for rotational movements was harder to recognize and less natural compared to other signals. The challenge of recognizing and responding to vibrotactile feedback for rotational adjustments has been noted in the literature [8]. We observed that the positions of vibration motors change during rotations as the arm rotates *within* the sleeve. This might have created some confusion for participants, although recognition accuracy was still satisfactory. However, it is recommended that the signal for rotational adjustments be moved off the forearm, and onto either the hand or upper arm.

The mean recognition accuracies for speed feedback, figure 4(a), are remarkable given the short training times. However, a significant difference was found between recognition accuracies, $\chi^2(7) = 17.1$, $p < 0.05$, indicating that some feedback signals were more difficult to recognize than others. From figure 4(a), we can observe that the recognition accuracies for 'Wrist L/R Decrease', 'Wrist L/R Increase', and 'Rotate CW/CCW Increase' are noticeably lower, although still satisfactory, compared to other signals. But subjective results don't reveal any difficulties with recognition (table 3, *Q1*), and participants found all speed feedback signals very natural (table 3, *Q3*). We speculate that this discrepancy arises not from detectability, but rather, participants' ability to perform the requested speed adjustments. Speed adjustments for wrist abduction/adduction and rotational movements might have been more difficult compared to other movements given their shorter range of motion. Indeed, we observed greater physical effort during these movements to achieve the requested speed adjustments; and several participants commented that the shorter range of motion made speed adjustments slightly more difficult.

The mean response time to positioning feedback is less than a second for training or testing, figure 3(b), with the exception of 'Rotate CCW'. The difference in mean response time between training and testing was not significant, $t(15)=0.689$, $p=0.5$, two-tailed (data normalized using $\log_{10}$), suggesting that either participants quickly adjusted to the feedback signals or longer practice times are needed to see larger gains in improvement. A significant difference was found between mean response times of signals, $\chi^2(7) = 15.3$, $p < 0.05$, indicating that reaction was slower for some signals compared to others. Indeed, figure 3(b) suggests higher response times for 'Elbow Down' and 'Rotate CCW', which correlates with recognition difficulties. The mean response time to speed feedback signals is less than 400 ms for training or testing, figure 4(b). The improved response times of speed feedback compared to positioning feedback is due to the near real-time operation of the system: in the case of speed feedback, participants had a small delay to prepare for the second start signal before making their speed adjustments. Similar to positioning feedback, the difference in mean response time between training and testing was not significant, $t(15) = -1.045$, $p = 0.312$, two-tailed (data normalized using $\log_{10}$). No significant

Table 1. Mean responses to system usability questions. Ratings are based on Likert scale: 1 (low) to 5 (high).

Questions	Mean	SD
1) How easy was it to put on the suit?	3.68	0.87
2) How easy was it to take off the suit?	3.43	1.15
3) How easy was it to perform the movements?	4.43	0.62
4) How comfortable was the suit?	3.87	0.95
5) How lightweight was the suit?	4.75	0.57
6) How silent were the suit's vibration motors?	3.37	0.95

Table 2. Mean responses to questions related to positioning feedback. Ratings based on Likert scale: 1 (low) to 5 (high).

Questions	Mean	SD
1) How easy was it to recognize the following feedback signals for changing position:		
• a) Elbow 'up' adjustment:	4.37	0.88
• b) Elbow 'down' adjustment:	4.00	1.09
• c) Wrist 'up' adjustment:	4.87	0.34
• d) Wrist 'down' adjustment:	4.68	0.47
• e) Wrist 'right' adjustment:	4.56	0.62
• f) Wrist 'left' adjustment:	4.62	0.50
• g) Rotate 'right' (CW) adjustment:	3.68	1.19
• h) Rotate 'left' (CCW) adjustment:	3.75	1.18
2) How easy was it to learn the following feedback signals for changing position:		
• a) Elbow 'up' adjustment:	4.50	0.73
• b) Elbow 'down' adjustment:	4.12	1.02
• c) Wrist 'up' adjustment:	4.93	0.25
• d) Wrist 'down' adjustment:	4.93	0.25
• e) Wrist 'right' adjustment:	4.87	0.34
• f) Wrist 'left' adjustment:	4.87	0.34
• g) Rotate 'right' (CW) adjustment:	3.87	1.14
• h) Rotate 'left' (CCW) adjustment:	3.93	1.12
3) How natural (intuitive) were the following feedback signals for changing position:		
• a) Elbow 'up' adjustment:	4.37	0.80
• b) Elbow 'down' adjustment:	3.81	1.10
• c) Wrist 'up' adjustment:	4.68	0.70
• d) Wrist 'down' adjustment:	4.68	0.70
• e) Wrist 'right' adjustment:	4.68	0.70
• f) Wrist 'left' adjustment:	4.68	0.70
• g) Rotate 'right' (CW) adjustment:	3.62	1.14
• h) Rotate 'left' (CCW) adjustment:	3.68	1.13

Table 3. Mean responses to questions related to speed feedback. Ratings based on Likert scale: 1 (low) to 5 (high).

Questions	Mean	SD
1) How easy was it to recognize the following feedback signals for changing speed:		
• a) Decrease speed for elbow… ('up'/'down'):	4.56	0.81
• b) Increase speed for elbow… ('up'/'down'):	4.81	0.54
• c) Decrease speed for wrist… ('up'/'down'):	4.62	0.80
• d) Increase speed for wrist… ('up'/'down'):	4.87	0.34
• e) Decrease speed for wrist… ('left'/'right'):	4.62	0.80
• f) Increase speed for wrist… ('left'/'right'):	4.87	0.34
• g) Decrease speed for forearm rotation ('left'/'right'):	4.62	0.80
• h) Increase speed for forearm rotation ('left'/'right'):	4.87	0.34
2) How easy was it to learn the following feedback signals for changing speed:		
• a) Decrease speed for elbow… ('up'/'down'):	4.68	0.70
• b) Increase speed for elbow… ('up'/'down'):	4.87	0.34
• c) Decrease speed for wrist… ('up'/'down'):	4.56	0.81
• d) Increase speed for wrist… ('up'/'down'):	4.75	0.57
• e) Decrease speed for wrist… ('left'/'right'):	4.50	0.96
• f) Increase speed for wrist… ('left'/'right'):	4.68	0.79
• g) Decrease speed for forearm rotation ('left'/'right'):	4.68	0.70
• h) Increase speed for forearm rotation ('left'/'right'):	4.87	0.34
3) How natural (intuitive) were the following feedback signals for changing speed:		
• a) Decrease speed for elbow… ('up'/'down'):	4.75	0.77
• b) Increase speed for elbow… ('up'/'down'):	4.81	0.54
• c) Decrease speed for wrist… ('up'/'down'):	4.75	0.77
• d) Increase speed for wrist… ('up'/'down'):	4.87	0.34
• e) Decrease speed for wrist… ('left'/'right'):	4.75	0.77
• f) Increase speed for wrist… ('left'/'right'):	4.87	0.34
• g) Decrease speed for forearm rotation ('left'/'right'):	4.75	0.57
• h) Increase speed for forearm rotation ('left'/'right'):	4.81	0.40

difference was found between mean response times of signals, $\chi^2(7) = 8.42$, $p = 0.297$, indicating that participants did not hesitate to make speed adjustments. This correlates with the positive ratings received for ease of recognition and naturalness. Lastly, the positive usability ratings of table 1 show that the system was easy to don/doff, comfortable and discreet; and very easy to move in and lightweight. Through open-ended response questions, participants commented that they liked the purpose and overall concept of the system; and overall, found the feedback signals easy to recognize and natural.

6. CONCLUSION AND FUTURE WORK

A novel vibrotactile positioning and speed feedback extension to an existing vibrotactile instruction set was proposed and evaluated. This makes several contributions: (1) The proposed approach bridges the divide between vibrotactile instructions and feedback, enabling the introduction of enhanced motor learning systems that scale well between novice and expert users who have different needs in terms of instruction and feedback delivery; (2) A novel feedback design for speed corrections, which participants found intuitive, and particularly appreciated the coherence of the signal between movements; and (3) A psychophysical evaluation of the proposed feedback signals to better understand the distinctness and naturalness of feedback signals by examining initial reactions and response times. Although this work did not explore vibrotactile instruction and feedback compatibility, their integration will be investigated as part of future work. The decision to focus evaluation solely on the proposed designs for vibrotactile feedback was motivated by the need for a thorough psychophysical evaluation before exploring human perception and usability of instructions with feedback.

As part of future work, we plan to further explore the perceptual and cognitive difficulties involved in switching between conceptual mappings, and evaluate different positioning feedback designs for rotational movements. A more long term goal is a longitudinal system evaluation within a real-world application such as physical therapy. Our first target application will be occupational therapy in which patients could benefit from a "take-home therapist" to practice and relearn movements away from the clinic. Vibrotactile instructions will provide a practice regimen, created by the therapist, targeting specific fundamental movements in need of continued practice at home and/or clinic. Motor rehabilitation often involves exercises to extend a patient's range of motion to what was normal. Vibrotactile feedback may be used to indicate when a specific range of motion (joint angle) has not been reached by the patient, helping to motivate the patient and indicate progress. The system will also alert the user when he or she is in danger of re-injury, such as when movements might be too fast. Toward the goal of a "take-home therapist", the main processing element (a laptop) will be replaced by a lightweight smartphone that can fit in a pocket.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Lederman, S. J., and Klatzky, R. L. 1987. Hand movements: A window into haptic object recognition. *Cognitive Psychology*, 19, 342-368.

[2] Kennedy, C. A., and Yoke, M. M. 2009. *Methods of Group Exercise Instruction*. Human Kinetics, Champaign, IL.

[3] Schmidt, R. A., and Wrisberg, C. A. 2000. *Motor Learning and Performance: A Problem-Based Learning Approach*. 2nd edition. Human Kinetics, Champaign, IL.

[4] Spelmezan, D., Jacobs, M., Hilgers, A., and Borchers, J. 2009. Tactile motion instructions for physical activities. *In Proc. of the 27th International Conference on Human Factors in Computing Systems*, 2243-52.

[5] Yang, U., and Kim, G. J. 2002. Implementation and evaluation of 'Just Follow Me': An immersive, VR-based motion-training system. *Presence: Teleoperators and Virtual Environments*, 11, 3 (June 2002), 304-23.

[6] Drobny, D., Weiss, M., and Borchers, J. 2009. Saltate!: a sensor-based system to support dance beginners. *In Proc. of the 27th International Conference Extended Abstracts on Human Factors in Computing Systems*, 3943–48.

[7] Grindlay, G. 2008. Haptic guidance benefits musical motor learning. *In Proc. of the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator systems*, 397-404.

[8] Lieberman, J., and Breazeal, C. 2007. TIKL: Development of a wearable vibrotactile feedback suit for improved human motor learning. *IEEE Transactions on Robotics*, 23(5), 919-926.

[9] Geldard, F. A., and Sherrick, C. E. 1972. The cutaneous 'rabbit': a perceptual illusion. *Science*, 178, 4057 (October 1972), 178 -79.

[10] McDaniel, T., Goldberg, M., Villanueva, D., Viswanathan, L.N., Panchanathan, S. 2011. Motor learning using a kinematic-vibrotactile mapping targeting fundamental movements. *In Proc. of the ACM International Conference on Multimedia*, 543-552.

[11] Bark, K., Khanna, P., Irwin, R., Kapur, P., Jax, S. A., Buxbaum, L. J., and Kuchenbecker, K. J. 2011. Lessons in using vibrotactile feedback to guide fast arm motions. *In Proc. of the IEEE World Haptics Conference*, 355-360.

[12] Wall, III, C., and Kentala, E. 2010. Effect of displacement, velocity, and combined vibrotactile tilt feedback on postural control of vestibulopathic subjects. *Journal of Vestibular Research*, 20, 61-69.

[13] Lindeman, R. W., Yanagida, Y., Hosaka, K., Abe, S. 2006. The TactaPack: a wireless sensor/actuator package for physical therapy applications. *In Proc. of the 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 337-41.

[14] Behnke, R. S. 2006. *Kinetic Anatomy*. Human Kinetics, Champaign, IL.