

TIKL: Development of a Wearable Vibrotactile Feedback Suit for Improved Human Motor Learning

Jeff Lieberman and Cynthia Breazeal - Regular paper

Abstract

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I. INTRODUCTION

People in physical rehabilitation, those with improper posture, and those wanting dance lessons all face a similar task – namely, motor learning. Most people benefit from a teacher who can give real-time feedback through a variety of channels: auditory (high level behavioral instructions), visual (by demonstrating the motion themselves), and tactile (by physically guiding the student). Although tactile feedback presents the most direct form of motor information, it is the most difficult for a teacher to give, especially while performing a task themselves. Further, due to human limitations, instructors cannot give tactile feedback over all human joints simultaneously.

This research proposes an extension to the human teacher – a robotic wearable suit that analyzes the target movement (that could be performed by the teacher) and applies real-time corrective vibrotactile feedback to the student’s body, simultaneously over multiple joints. After a period of acclimation, the student can utilize this novel high bandwidth vibrotactile information to more quickly and deeply learn new motor skills. We describe this system as TIKL: Tactile Interaction for Kinesthetic Learning.

A. Purpose, Motivation, Applications

Real-time feedback about one’s performance is the most important factor in learning new motor skills [1] (e.g., visual, auditory, and tactile modalities). Tactile feedback is unique in that it directly engages our motor learning systems. There is no need to map the teacher’s performance onto ourselves, as is the case with visual feedback. Auditory feedback is abstract and a mental model needs to be created in order to properly parse the information. Due to this, people are often better at performing an action properly than teaching

another to do so. Therefore, if we find methods by which to take teacher performance and apply it directly to students motor learning systems, we may avoid the pitfalls normally associated with teaching skills to another.

The goal of this system is to become a low latency, full-time, highly parallel robotic motor skills teacher that can provide constant motor-system feedback to the student as he or she attempts to learn new motor skills.

B. Project Scope and Overview

The feedback system consists of four main modules shown in Fig. 1. The first module shows the teacher and student. The teacher performs a movement that the student tries to mimic. Their performance is tracked optically by a Vicon motion capture system. Results from tracking are fed into our software that compares the performance of the student and teacher to generate feedback commands for the student. These feedback signals are then sent to the wearable vibrotactile feedback suit, worn by the student. Joints moving in error will receive vibrations proportional to the amount of error. When the student’s body is in the right position feedback is zero. Direct tactile feedback indicates the discrepancy, wherever the student’s body is different than the teacher’s. The rationale and implementation of this system are presented next.

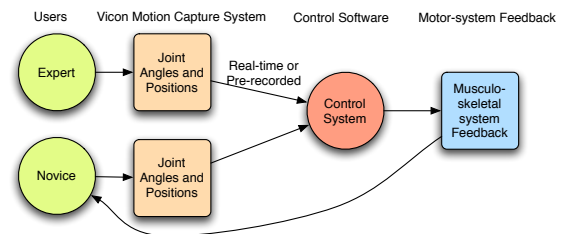


Fig. 1. Modular flow for the motor learning feedback wearable system.

II. MOTOR LEARNING

A. Motor Learning, Feedback, and Touch

Feedback is crucial to perform motor skills well [2], [3]. Performance is improved by both the specificity of feedback, and its immediacy [4]. No other independent variable is thought to affect one’s performance as much as immediate feedback.

The skin is sensitive to many qualities of touch [5]. Skin is specifically responsive to frequencies of roughly 250 Hz. Vibrotactile actuator size influences frequency sensitivity. Other factors such as low frequency oscillation (LFO) envelopes, sequences, and our adaptation to touch impulses, are discussed at length in [5].

We utilize an effect known as the ‘cutaneous rabbit’, more formally known as sensory saltation [6]. A sequence of properly spaced and timed tactile pulses will be processed as if distributed “with more or less uniform spacing, from the region of the first contactor to that of the [last].” This allows us to utilize vibrotactile actuators as a means to directly communicate errors of joint angles. In addition, superimposing saltative sequences can communicate rotational errors.

B. Previous work: Virtual Reality Training and other Tactile Inventions

Virtual reality (VR) environments have been shown to improve motor learning by providing augmented feedback. Often VR displays overlay the student’s performance with the desired movement, that provides an “intuitive and interpretable form... sharing the same spatial frame of reference [7].”

VR environments are useful because they emphasize the differences between the subject and reference movements and highlight desired trajectories in an understandable frame [9]. In some complex tasks, VR training actually exceeds training from a human expert [8]. VR training at times shows more robustness to cognitive interference phenomena, such as performing a task while being distracted with unrelated behaviors [10]. Furthermore, VR training may be retained longer than regular training [11].

Tactile actuators were originally developed for sensory substitution, rather than for sensory augmentation. Prior works have used tactile actuators to transmit speech information to the deaf and blind community through the skin. Similar work has shown scaled architectures of almost 1000 DOFs, for video tactile displays. However, touch has not yet been used to augment our somatosensory learning systems. Promising work has hinted at the utility of tactile feedback for neurological trauma rehabilitation. But as of yet, research has focused on the application of torques on subjects’ joints.

Patients in neurological literature (such as HM [12]) have lost the ability to form new long-term memories, but can still build new motor skills. This research posits that our brain processes motor learning separately from other conscious types of learning — indicating that we may be able to eventually train users to accept this feedback subconsciously to learn motor skills. Corrections may become an automatic muscle reflex, instead of a conscious mediation.

III. SYSTEM IMPLEMENTATION

Our system for motor learning is made up of optical tracking, tactile actuators, feedback software, and hardware for output control. These systems are each described below. For a more thorough explanation, see [13].

A. Vicon Tracking System for Subject Tracking

Vicon Inc. has designed the most accurate motion capture system currently available commercially, with millimeter accuracy in 3-d space over a large workspace. It functions through the use of roughly one dozen high-speed infrared

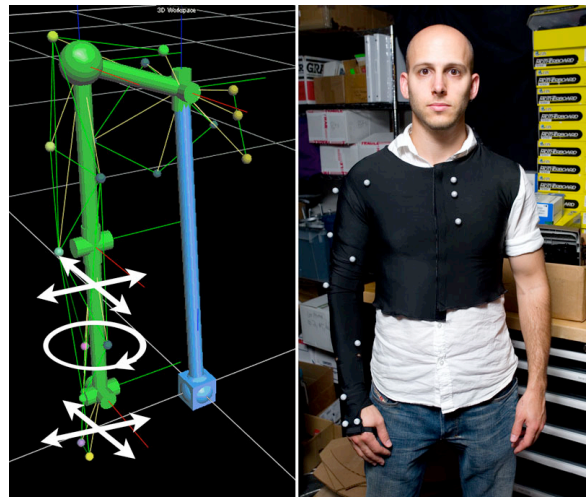


Fig. 2. Marker placement of the joints on the right arm, indicating the DOFs regulated in the experiments.

cameras, matched strobes, and custom hardware. Reflectors placed on subjects are illuminated by the strobes, and the cameras use filters such that only those frequency reflections are visible. By calibrating the software to know the cameras’ locations, 3-d models of all markers can be inferred from the individual 2-d camera views, and the overconstraint of many cameras increases the positional accuracy. Skeletal models of subjects are made in software with known marker locations, and those models are given a least-error kinematic fit in real-time. Joint angle information must then be calculated from the known joint positions. Figure 2 shows a subject wearing our motor learning suit with reflecting markers, and the associated model with known marker positions and skeletal kinematic fit. The markers’ placement and the calculated joint angles are used to find the five observed joints: wrist flexion/extension, wrist abduction/adduction, forearm rotation, elbow flexion/extension, and upper arm rotation.

Because all subjects have slightly different joint lengths and offsets, but the same skeletal structure, the Vicon software provides a calibration routine to be run on each subject. The subject runs through a set of movements as they are tracked, and the software finds the joint lengths and marker offsets to match the subject to the skeletal template in order to minimize error. Figure 3 shows the results of the calibration on one subject, comparing the template nearest fit to the actual marker positions.

It is worth noting that the Vicon system is very expensive and bulky. It is not intended as a final solution to the body tracking problem, as it is too expensive to be practical for most users. However, it offers the accuracy needed for a proof of concept, and was an available tool for our initial experiments. In the future, it is likely that centralized sensors such as gyros and accelerometers would provide such bodily measurements without such a prohibitive expense.

B. Tactaid Tactile Actuators

Vibrotactile actuation was chosen as a feedback mechanism for several reasons. Torque for feedback on joints is

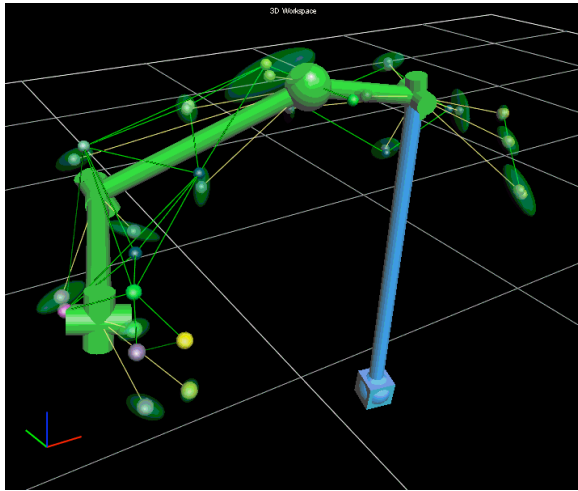


Fig. 3. Result of Vicon subject calibration. Each marker is shown twice, once in its observed position, and one as a best fit to the kinematic skeletal model of the subject, with translucent ovals measuring the variance in each marker uncertainty.

cumbersome and requires higher power, lowering portability for use in real learning environments (e.g., a dance class). Electro-tactile stimulation can be dangerous and/or painful. The tactile actuators shown in Figure 4 (from Tactaid) were chosen for their compact size, high output power density, resonant frequency of 250 Hz (for maximum detection by humans) and previous history, of use in speech-to-tactile translation. Typical vibrating motors, used in cellphones and similar products, function via an off-center weight spun on a DC motor. This requires high spin-up times to reach desired amplitudes and makes the control of amplitude and frequency linked together. The Tactaid actuator functions as a resonant actuator, utilizing a coil attached to the end of a resonant spring, turned on and off manually at the resonant frequency of the mass-spring combination. This allows the frequency to be controlled independently of amplitude, and allows very quick ring-up and ring-down times. The high bandwidth response is ideal for the quick feedback responses needed in motor skills. Figure 4 shows the physical vibrators.

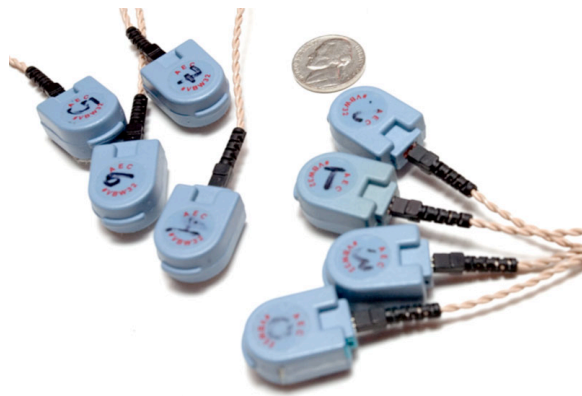


Fig. 4. The 8 Tactaid vibrotactile actuators used in our initial motor learning feedback experiments. A nickel is shown for scale.

Figure 5 shows where the actuators are placed on the right

arm to regulate the five DOFs in our study. Slits cut into the suit allow the actuators to be slid inside for direct skin contact, and velcro fixes them in place. They are placed at quadrants around each joint, to allow proportional feedback along specific joint angles and projections. All actuators are placed so that the direction of vibration is perpendicular to the plane of the skin.

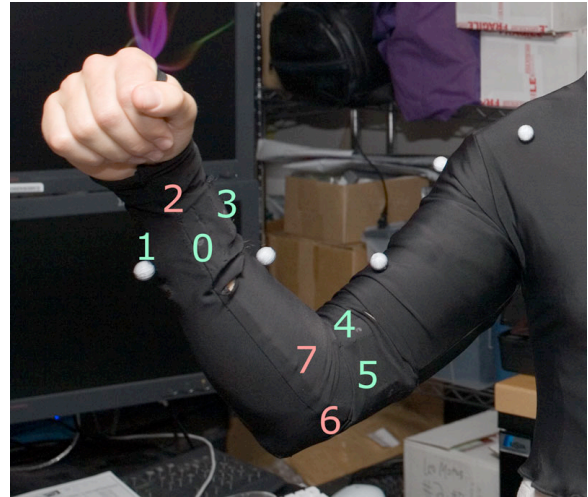


Fig. 5. Figure showing the placement of the 8 tactile actuators used in experiments. Red indicates obstructed view of the actuators.

In order to regulate the joint rotation of the forearm, we use the sensory saltation phenomenon described previously above. By sequentially pulsing the four wrist actuators quickly clockwise or counter-clockwise, the subject is given the sensation that a continuously rotating signal is being applied to the wrist, which is used to indicate a rotational error signal for that joint. Details of signal generation are discussed in Section III-C.

C. Control Software

The control software determines what vibrotactile signals should be sent to the actuators, to provide user feedback during their performance. As well as this output, it also saves subject performance for later analysis.

Vicon data is streamed from both the student and teacher. Joint angles are derived from marker tracking. For each joint, an error signal of

$$\Delta\theta_{error} = K_p(\theta_{teacher} - \theta_{student}) \quad (1)$$

is computed, where K_p represents a proportionality constant chosen for each joint to allow subjects to feel a proper range of motion given typical movement levels of the joint. Feedback signals generated through Equation 1 allow the error to be represented from the reference teacher's motion.

It is worth noting that in the current system *only joint angles* determine the errors. In general use, this is not necessarily the manner in which subject error should be found. In object-oriented tasks (such as lifting a glass), the end-effector is likely to be more important than the joint angles since it determines the success of the task. Most likely,

some superposition of end-effector positions, joint angles, and dynamic properties is needed to adequately gauge subject performance in general contexts.

As an example, consider feedback given to the wrist joint. For feedback of wrist bending, actuators 0 and 2 (shown in Figure 5) are utilized. If the wrist is bent too far inward (compared to the teacher motion) then actuator 0 is vibrated more and more strongly as the error is increased. Similarly, if the wrist is bent too far outward, actuator 2 is vibrated, with the amplitude determined by Equation 1. Overall, this feels as if there is a vibrating ‘force field’ around the correct motion, and any deviation from that desired motion creates a restoring vibration. This tells the user the direction to travel to correct the error, without imparting any force to the joint to move it.

D. Control Hardware

Custom hardware was fabricated to allow for 8 channels of synchronous high frequency PWM vibrational signals to be sent to the user, in a small form factor and at low power. The hardware receives error signal updates over a serial line at roughly 30 Hz, in 16-bit form, over all five joint errors. A microcontroller transforms this error signal into a square wave at 250 Hz. The average amplitude of this square wave is created by multiplying the 250 Hz envelope by a 40 KHz square wave of duty cycle equal to the error, scaled so that maximum error for each joint equates to a full 100% duty cycle wave.

IV. EXPERIMENTAL SETUP AND RESULTS

Our initial experiment examined motor learning performance of 40 subjects on 5 DOFs of their right arm. The experiment is designed to determine if this type of tactile feedback accelerates and deepens students’ learning of new motor skills. To test this, we split the 40 subjects into two even groups: the first 20 receive visual feedback of tasks they are told to imitate, and the second 20 receive visual plus additional tactile feedback from the vibrotactile actuators. This experimental protocol was reviewed and approved by the institutional review board of MIT¹.

A. Protocol

Subjects were brought into the lab space. A roughly 10’x20’ work-area is covered by the Vicon optical tracking system. Each subject is run through a ten minute calibration routine to calibrate the template models to their body. The subject sits down at a desk facing a computer screen. All users have the vibrotactile actuators installed, even if not used, so that the suits otherwise feel the same. The typical user setup for experimentation is shown in Figure 6.

To acclimate users to the vibrotactile feedback, a series of still images is shown on the video screen, and subjects are told to copy them as quickly and precisely as possible. Each image is shown for roughly five seconds before the next, and depicts an over-the-shoulder view of a teacher holding a

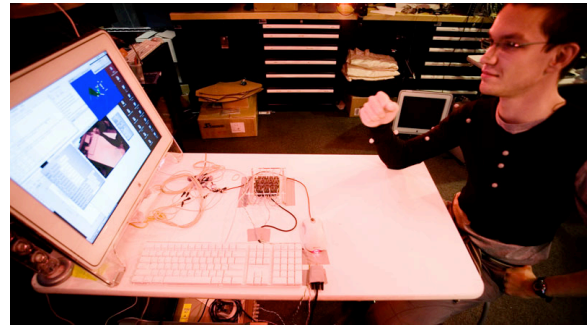


Fig. 6. A typical user setup, with the user sitting across from the display screen.

fixed position with their right arm. During that time, the users experience tactile feedback for the first time, and so are given time to become acclimated to the type of feedback. Each time a new image is shown, the tactile feedback immediately begins reporting the new joint angle errors on the subject’s body, and we measure how accurately and quickly all users reach the desired location.

After this phase of still images is shown, a set of target motion videos lasting 3-10 seconds in length are shown. To analyze the students’ learning over time, we repeat videos 6 times, giving users a chance to anticipate actions and memorize them. Actions are short enough to be retainable in short-term memory, but these go from extremely simple 1-DOF motions, to very complex motions using all 5 DOFs, moving quickly enough that no user should be able to represent them completely accurately. Example motions of both types are shown in Figures 7 and 8, respectively; the first shows a simple motion of only the elbow, whereas the second displays a very complicated motion involving all 5 joints.



Fig. 7. A simple motor learning video. Compare to Figure 8

After roughly 20 minutes of the motion video phase of the experiment, the user is disconnected from the system and given a short questionnaire to assess the usefulness, comfort level, and readability of the vibrotactile system. This is scored on a 1-7 Likert scale from ‘strongly disagree’

¹MIT COUHES approval #0603001679



Fig. 8. A difficult motor learning video. Compare to Figure 7

to ‘strongly agree’. A free section at the end allows open comments.

B. Results

According to the questionnaire, all users, felt reasonably comfortable wearing the device (5.7 out of 7). All users felt they improved their performance over time (5.6), but the tactile group noted that this required more conscious effort (5.3 tactile versus 4.4 visual only). No users felt significant fatigue from the experiment, but users with tactile feedback (3.7) felt more fatigued than the visual feedback alone (2.7).

Some questions were asked only of the tactile feedback group. These users felt very strongly that over time they would improve their ability to use the feedback (6.2), but that the specific method of feedback did not significantly help (4.9). They felt strongly that they received joint angle information from the device over time (6.4) and joint rotation information, although slightly less so (5.8).

Several viewpoints were shown in open comments. Some people felt slight discomfort in the seating and elbow positioning arrangement, and some did not seem to know how to respond to the vibrational signals, at times. Many people had a positive reaction about the utility of tactile feedback for this type of motor learning, remarking that it was “awesome,” “very interesting,” and “really fascinating.” Many also pointed out specific room for improvement of the type of feedback given, such as a dead zone of feedback when people are doing well enough, or focusing on a single axis showing the most joint error at a time, to allow users to fix their behavior in order of most to least worst joint.

In still image tracking, users with visual feedback would settle on their final position after roughly 1.5 sec, but those with tactile feedback would continue to refine their motions over the next four seconds. Error at all times is calculated in a joint-by-joint sense,

$$\epsilon(t) = \sqrt{\sum_i \epsilon_i^2(t)}, \quad (2)$$

where i varies over all joints in the system and ϵ_i represents the joint angle error of joint i . Users were explicitly told to try to mimic joint angles, as opposed to another metric such as end effector position, so this is a valid error calculation of performance.

Analysis of frame-by-frame performance during the motion videos shows that the addition of tactile feedback enhances performance at almost all times. The only exception is at the initial moments of a new video where users react more quickly without tactile feedback. Given the short experiment time, it is likely that early on subjects with tactile feedback did not yet have a chance to acclimate to the system. Subjects utilizing this new feedback had an overall a reduction of error (as calculated in Eq. 2) of 21%, highly statistically significant ($p = 0.015$).

To further analyze performance, Equation 3 calculates a ‘trial error’ by summing individual frame errors over each full repetition of a video, as

$$\Delta_n = \int_{t_n}^{t_{n+1}} \epsilon(t) dt, \quad (3)$$

where $[t_n, t_{n+1}]$ represents the time interval of the n^{th} trial. Figure 9 shows the relative trial performance of the two groups. Notably, the addition of vibrotactile feedback *at all times enhances performance, independent of task difficulty.*

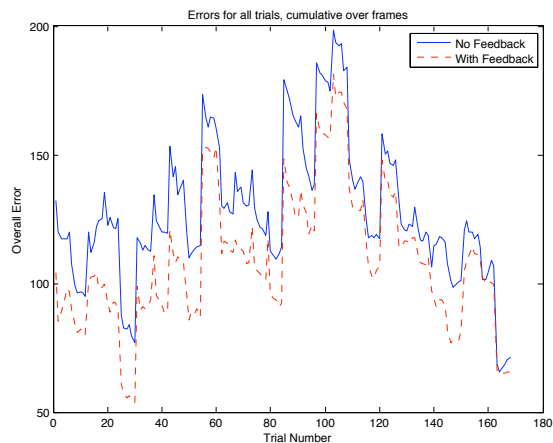


Fig. 9. Measure of errors integrated over a full trial, averaged over all users. Note that at all times performance is improved with the addition of tactile feedback.

1) *Hinge and Rotary Joint Improvements:* The information given to the hinge joints (wrist up/down, wrist left/right, and elbow open/close) is easier to process by humans than rotational data (wrist rotation and upper arm rotation), because the rotation data is delivered indirectly (either through saltation, described in Section III-B, or by another technique). Because of this extra processing required, it is natural to assume that users will be more adept at learning how to process the hinge joint information. To investigate this further, we split the preceding analysis into hinge and rotary joint styles.

Figures 10 and 11 show the results of the same analysis on hinge and rotary joints, respectively. Separation of this

data yields useful information. As is evident graphically, rotational joints are not improved with any statistical significance. However, the hinge joints (three of the five) are improved by an average of 27%, very statistically significant ($p \leq 0.01$).

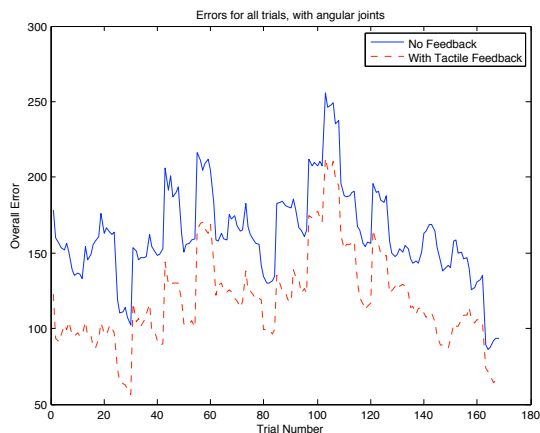


Fig. 10. Measure of errors integrated over a full trial, averaged over all users, only utilizing joints with hinge-angle feedback. At all times, performance is significantly improved.

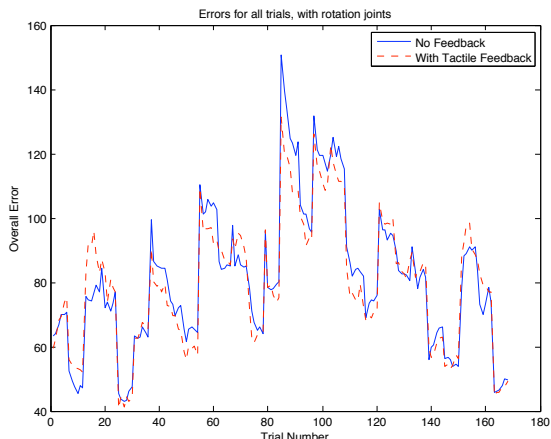


Fig. 11. Measure of errors integrated over a full trial, averaged over all users, only utilizing joints with rotary-angle feedback. Performance is not significantly altered

Below, we analyze how the different joint types are effected by repeated trials.

C. Learning over repeated trials

We are interested in how subjects improve over multiple viewings of each video. Therefore, we average all users' performances on the n^{th} trial of all movies to get a metric of " n^{th} trial performance." This is shown explicitly in Equation 4,

$$\Delta T_i = \frac{1}{SM} \sum_{s=1}^S \sum_{m=1}^M \Delta_{sm}, \quad (4)$$

where s represents the subjects and m represents the different movies, of total number S and M , respectively, and Δ_{sm} represents the error of user s during trial i of movie m .

We compute a curve representing subjects' errors in imitation over six trials. We make the assumption that their performance will approximate a fading exponential, as they improve over time, of the form

$$\Delta = a + be^{-cx}, \quad (5)$$

meaning that they learn at learning rate c , and settle into a steady-state error a . We fit our data to the form of Equation 5 using a linear least squares sitting form, the results of which are shown in Figure 12.

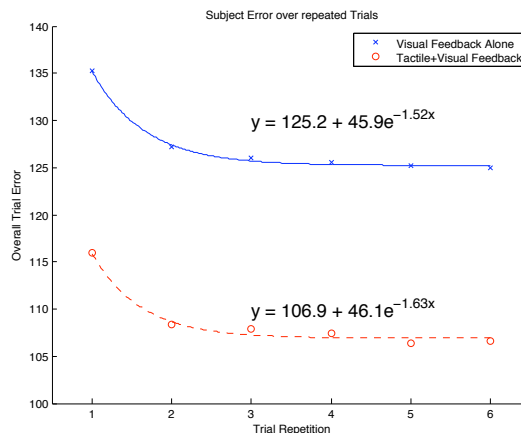


Fig. 12. A measure of subject improvement over the six study trials for each movie. The data is fit to a fading exponential model.

The average subject error in recreating novel motion (on the first viewing) is reduced by roughly 11%, indicated by $a + be^{-c}$. However, even given a lower starting error, the learning rate (given by parameter c , the exponential time constant) is improved by 7%. Finally, a represents steady-state error, which in this six-trial experiment was improved by 15% due to the addition of tactile feedback. This steady-state error represents how well a user eventually performed on the task, and is therefore a good measure of a subject's overall performance. Each of these results is statistically very significant ($p < 0.01$).

Once again we observe the differences in this behavior over the different joint types. By splitting the analysis into hinge and rotary joint types, our results bifurcate quite dramatically, as shown in Figures 13 and 14, respectively.

Error improvement is reduced, almost negligible, on the difficult-to-parse information of rotational joints. Differences in behavior are mild. However, differences in performance for hinge joints are very statistically significant ($p < 0.01$), and are very large. Initial viewing performance (denoted as $a + be^c$) is improved by 25%. Steady-state (long term performance) error is reduced by 27.4%. Analyzing learning rate becomes more difficult with such a large performance ability margin, because even with a higher learning rate, there becomes less to 'learn,' in terms of further reducing error. If we ignore this, the learning rate appears to actually decrease by 6%. However, if we offset this by the difference in performance ability (multiplying by the ratio of errors), this learning rate appears to improve by 23%.

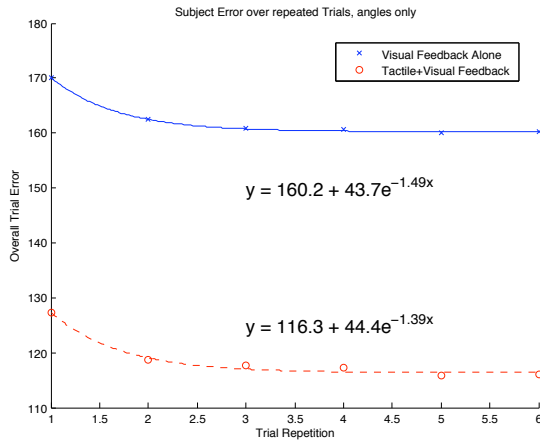


Fig. 13. Fading exponential fit of only hinge-angle data. A significant improvement in error is illustrated.

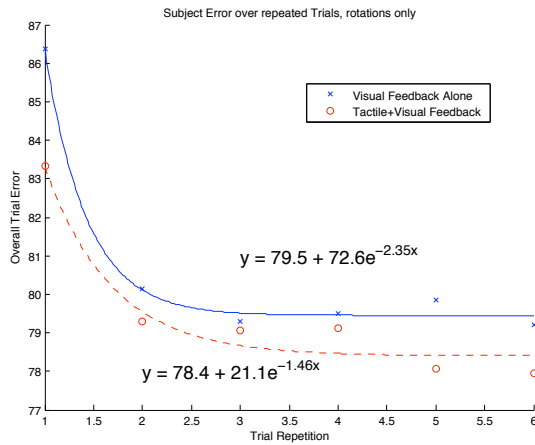


Fig. 14. Fading exponential fit of only rotary-angle data. No statistically significant changes in behavior are found. Note the change in scale.

To sum up, we provided subjects with tactile feedback on 5-DOFs of their right arm, as they tried to mimic teacher motions. The method by which feedback was delivered was not optimized. The method of feedback was not felt to be automatic to understand by the subject, and positions of tactile actuators were not placed exactly. Further, we provided only linearly proportional feedback over all joints. However, with no optimizations, we note a statistically very significant gain of 15% in subjects' performance, and accelerated learning of 7%. Looking at joints for which we delivered information that is easier to parse by subjects, improvements are even more dramatic, showing performance gains of 27% and possible accelerated learning of up to 23%, when readjusted for overall errors.

Given the nature of the experiment (i.e. joint number, task difficulty, and time to acclimate to the system) and the type feedback given, we expect the numbers to improve as we hone our methodology, and move towards a full-body real-activity system. We have shown an initial proof of concept, whereby we already notice significant gains in performance. In more complex motor learning tasks, we may notice much larger performance gains.

V. FUTURE WORK

We have noted a major change in performance through the addition of tactile feedback to motor learning acquisition. However, there are many improvements to be made, and possible pitfalls in future research, described below.

A. Problems and Improvements

One problem with deploying this current system in the real world is the use of a very expensive optical tracking system, which limits accessibility to those with a hefty budget. Alternative position-sensing systems should be researched to find non-localized sensing that is inexpensive, so users could change locations for ease of use. These ideas are being explored by [14] et al. Also, when the optical markers are temporarily occluded, the Vicon system has difficulty finding accurate kinematic solutions without being reset.

The development of smaller more powerful tactile actuators will prove useful, if this system is intended to be used on an entire body, which would necessitate on the order of 100 tactile actuators. The weight of these actuators may prove distracting, and in the least, bulky. Ideal marker placement remains another interesting subject for future research.

Currently the performance gains from hinge-type joints are very noticeable and dramatic; however the gains on rotation joints such as the wrist yield little to no significant improvements. More time and research must be done to find adequate methods of feedback on these joints, so they are easier for subjects to parse. That being said, there is no *a priori* reason to believe that subjects would be less adept at rotational joint learning. We are therefore hopeful that the more significant gains will extend throughout the body.

We currently do not know whether scaling such a system to higher parallel DOFs will result in changed performance. How many vibrotactile feedback channels can be utilized in parallel remains an open question. It is possible that we will have no problems scaling and improvements will increase, but if human attentional limits are an issue, alternative training regimens must be researched.

We also do not know the best metrics by which to gauge goal-oriented performances. For tasks such as those tested, joint angle error is an adequate method by which to judge performance. However, in many other events, it is the end-effector position, end effector dynamics, or a combination of these and other factors, that contributes to a successful task completion. Much more research must be done to enable mapping of a teacher onto a student, with these metrics in mind.

Finally, we do not know anything about the long-term implications of such a system. In a sense, the added complexity of full body feedback means that subjects will require longer to feel comfortable. However, no research has been done to quantify how much. Similarly, not all interactions with the teacher need to occur in real-time. The fact that the system can record motion information may prove important, as users could playback motions at whatever tempo they desired. The speed could even be automatically increased based on performance improvements, with subjects working up speed based on their understanding of motions.

B. Suggested Future Research and Applications

One avenue of exciting research is to test the extent to which this feedback can be used in training with no visual feedback whatsoever. This could be useful in training motion to the blind. Posture, sports and dance are the most obvious applications for this device. The market for golf swing training alone is enormous, but will require much more knowledge of feedback based on human dynamics.

Another application for motor learning improvements is neurological rehabilitation, such as post-stroke rehabilitation. Given the VR training improvements mentioned above, it is likely that this extra stimulation would engage subjects into rehabilitating faster and more deeply, but experiments will be needed to determine the validity in this conjecture.

An exciting peripheral application of motor learning is in the retraining of improper posture, the source of many problems such as back and muscle pain or injury. A pared-down version of this system could allow for static motor learning, so that people can train themselves to sit and stand properly in a much shorter time. This would be akin to having someone looking over your shoulder and correcting your posture at all times.

There are many avenues for future research, and many possible applications of this type of feedback to our daily lives. Future work must hone the methodology, improve the technology, and test the limitations of such techniques for the benefit of our daily enjoyment and for our lifetime health.

VI. CONCLUSIONS

We have found that the addition of tactile feedback to motor training induces a statistically very significant change in performance. It lowers real-time errors by up to 27%; learning rate is improved by up to 23%; and steady-state learning errors, the measure of performance over time, are improved by up to 27% over flexion joints. Subjects with feedback showed higher level of attention, correcting their motions at times when those without tactile feedback stood idle. Importantly, this all occurred while users felt there was no significant loss of comfort through the addition of the wearable.

It is possible that over long-term usage, users may become accustomed to the system, and the more complex feedback paths may become subconscious. We may eventually be able to learn these motions faster, deeper, without even realizing that we are doing so.

VII. ACKNOWLEDGMENTS

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REFERENCES

- [1] E. Bilodeau and I Bilodeau, "Some effects of introducing and withdrawing knowledge of results early and late in practice", *Journal of Experimental Psychology*, vol 58, 1959, pp 14244.
- [2] E. Bilodeau and I Bilodeau. "Motor-skills learning", *Annual Review of Psychology*, vol 12, , 1961, pp 243280.

- [3] J.S. Brown, "A proposed program of research on psychological feedback (knowledge of results) in the performance of psychomotor tasks", *Research Planning Conference on Perceptual and Motor Skills, AF HRRC Conf. Report 49-2*, 1949, pp 8187.
- [4] R.B. Ammons, "Effects of knowledge of performance: a survey and tentative theoretical formulation", *Journal of General Psychology*, 1956, pp 27999.
- [5] Ian R. Summers Ed. *Tactile Aids for the Hearing Impaired*, Whurr Publishers, London, 1992.
- [6] F.A. Geldard and C.E. Sherrick, "The Cutaneous 'Rabbit': A Perceptual Illusion", *Science*, vol 178, 1972, pp178179.
- [7] M Holden. "Virtual environments for motor rehabilitation: Review", *CyberPsychology and Behavior*, vol 8, no 3, 2005.
- [8] E Todorov, R Shadmehr, and E Bizzi, "Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task", *Journal of Motor Behavior*, vol 29, pp 147158, 1997.
- [9] E Bizzi, F.A. Mussa-Ivaldi, and R. Shadmehr, "System for human trajectory learning in virtual environments", *U.S. Patent No. 5,554,033*, 1996.
- [10] FD Rose, E.A. Attree, and B.M. Brooks, "Training in virtual environments: transfer to real world tasks and equivalence to real task training", *Ergonomics*, vol 43, pp 494511, 2000.
- [11] B Brooks, J.E. McNeil, and F.D. Rose et al. "Route learning in a case of amnesia: a preliminary investigation into the efficacy of training in a virtual environment", *Neuropsychological Rehabilitation*, vol 9, pp 6376, 1999.
- [12] WB Scoville and B Milner, "Loss of recent memory after bilateral hippocampal lesions", *J Neurol. Neurosurg. Psychiat.*, vol 20, no 11, 1957, pp 11-21.
- [13] J Lieberman, "Accelerated and Improved Motor Learning and Rehabilitation using Kinesthetic Feedback", Master's Thesis, Massachusetts Institute of Technology, 2006.
- [14] A Howard and MJ Mataric, "Cover Me! A Self-Deployment Algorithm for Mobile Sensor Networks", *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA2002)*, 2002.



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