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Development of a Wearable Vibrotactile Feedback Suit for Accelerated Human Motor Learning

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***Abstract*— When a human learns a new motor skill from a teacher, they learn using multiple channels: They receive high level information aurally about the skill, visual information about how another performs the skill, and at times, tactile information, from a teacher's physical guidance of the student. This research proposes a novel approach, the application of this tactile feedback through a robotic wearable system, while a student tries to learn from a teacher. Initial tests on a 5-DOF robotic suit show a decrease in motion errors of over 20%, and an accelerated learning rate of 7%, both conservative given the system setup and statistically very significant ($p \leq 0.01$). This research is intended in use of sports training, motor rehabilitation after neurological damage, dance, postural retraining for health, and many other contexts.**

I. INTRODUCTION

People in physical rehabilitation, those with improper posture, and those wanting dance lessons all face a similar task. Motor learning is something we experience from when we learn to walk, to when we try to emulate professional sports players on the golf course, to when we recover from stroke. 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; and due to human limitations, they cannot give tactile feedback over all human joints.

This research proposes an extension to the human teacher - a robotic wearable suit, real-time and over many degrees of freedom (DOFs) of the body, that analyzes the teacher's motions, and applies corrective vibrotactile signals to the student's body. After a period of acclimation, the student can utilize this new high bandwidth information to more quickly and deeply learn new motor skills, from proper posture to a better golf swing.

A. Purpose, Motivation, Applications

Real-time feedback about one's performance is the most important factor in one's ability to learn motor skills [1], occurring through visual, auditory, and tactile pathways. Tactile feedback is unique in one manner, being the only internal direct feedback, applied to our own bodies. Furthermore, when we perform an action properly, our proprioceptive senses take effect, and motor memory begins to aid learning.

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, often teachers are 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, 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, by giving constant motor-system feedback to the user, as subjects attempt to learn new motor skills.

B. Project Scope and Overview

The feedback system consists of four main modules, shown in Fig. 1. The first are the two types of user, the teacher and student. Their performance is tracked optically by a Vicon vision system. Results of this tracking are fed into software, comparing performances and generating desired feedback commands to the student user, based on their attempt to mimic the teacher. These feedback signals are then sent to the wearable vibrotactile feedback suit, worn by the student, which signals them to performance errors. These sections and the justifications behind their implementation are discussed in more detail below.

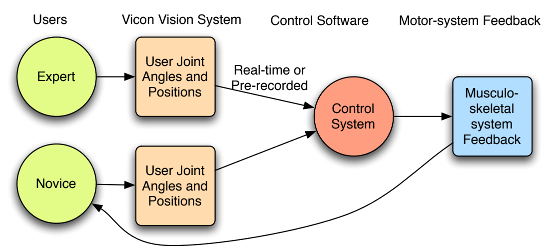

Fig. 1. Modular flow for the motor learning feedback wearable system.

Whatever joint is in error will vibrate proportionally to the amount of error. When one's body assumes the right position, there are no feedback signals, but wherever a subject's body is different than the teacher's, direct tactile feedback indicates the discrepancy.

II. MOTOR LEARNING

A. Motor Learning, Feedback, and Touch

Feedback is crucial to levels of performance in motor skills[2], [3]. The more specific feedback, and the shorter

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the time delay, the better the performance [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 will utilize an effect known as the 'cutaneous rabbit', more formally as sensory saltation. 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] [6]." This will allow us to utilize vibrotactile actuators directly for showing errors of joint angles, and using multiple actuators sequenced saltatively to show 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. A VR display overlays subject performance with desired goals, which 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 by highlighting 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]. It is worth emphasizing the main differences between this current system and a VR system: this system utilizes tactile feedback, directly activating the motor system of the brain, to increase learning depth and rates, and it does so while the user [and teacher] are able to co-exist in their natural environment.

Tactile actuators were originally developed for sensory substitution, which yields a possible explanation for why they have not yet been used for sensory augmentation. Early work transmit speech information to the deaf and blind community through the skin. Similar work has shown scaled architectures of almost 1000 DOFs, allowing video tactile displays, touch has not been used to augment our somatosensory systems. Promising work has hinted at the utility of tactile feedback for neurological trauma rehabilitation, but as of yet has necessitated 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 still can build new motor skills, suggesting that our brain processes motor learning in a separate area of the brain than other conscious types of learning - this indicates that we may be able to eventually train users to accept this feedback subconsciously, while still allowing its efficacy to show through. Corrections may become an automatic muscle reflex, instead of a conscious mediation.

III. SYSTEM IMPLEMENTATION

This new system for motor learning is made up of optical tracking, tactile actuators, and 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*

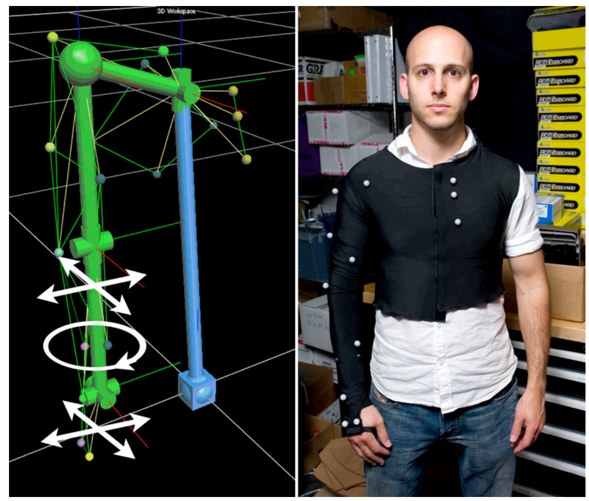

Fig. 2. Marker placement of the joints on the right arm, indicating the DOFs regulated in the experiments.

The Vicon tracking system provides millimeter accuracy on infrared reflective markers, over a large workspace. In this context, markers placed on a variety of known locations of a subject's body gives highly accurate joint position and angle sensing, provided at 100 Hz. Fig 2 shows the author wearing a suit with markers, and the associated kinematic data fit. This is used to determine the five observed angles: wrist in/out, wrist right/left, forearm rotation, elbow in/out, and upper arm rotation.

B. *Tactaid Tactile Actuators*

Vibrotactile actuation was chosen as a feedback mechanism for several reasons. Torque for feedback on joints is cumbersome and requires higher power, lowering portability for use in real learning environments [eg. a dance class]. Electro-tactile stimulation can be dangerous and/or painful. The tactile actuators shown in Fig. 3, from Tactaid were chosen for their compact size, high amplitude of vibration feedback, resonant frequency of 250 Hz [for maximum detection by humans] and track record, having been created for speech-to-tactile translation. The high bandwidth response allows the actuator amplitude to be modulated very quickly, in contrast to a cell-phone vibrator, which consists of an off-axis weight on a rotary DC motor.

Fig. 4 shows where the actuators are placed on the right arm to regulate the five DOFs. Slits cut into the suit allow the actuators to be slid inside for direct skin contact, and internal velcro fixes them in place. They are placed at quadrants, to

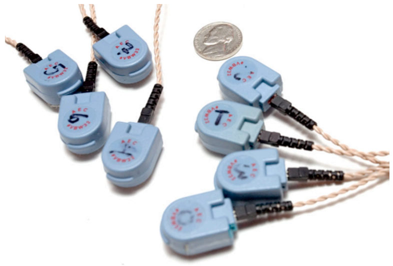

Fig. 3. The 8 Tactaid vibrotactile actuators used in the initial motor learning feedback experiments. Nickel shown for scale.

allow proportional feedback along specific joint angles and projections.

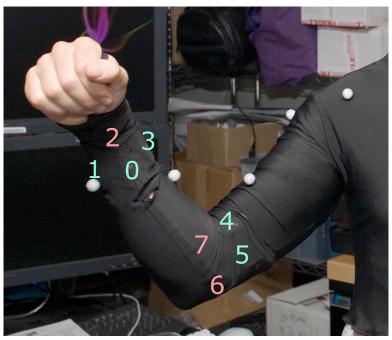

Fig. 4. Figure showing the placement of the 8 tactile actuators used in experiments. Red indicates obstructed view of the actuators.

In order to regulate the joint rotation of the forearm, we use the sensory saltation phenomenon described 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 arm, which is used to indicate a rotational error signal. Details of signal generation are discussed in Section III-C.

C. Control Software

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

Two input streams are given of Vicon subject data - teacher and subject. From marker tracking, joint angles are derived, and for each joint, an error signal of

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

is found, 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 Eq. 1 allow error to be represented from the reference 'teacher' motion, shown in the aforementioned research to be the most promising currently known approach.

It is worth noting that as of now, it is *only joint angles* that determine the errors, but 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 position could be argued to possess more importance than joint angles, since it determines success at the task. Most likely, some superposition of end-effector positions, joint angles, and other heuristics is needed to adequately gauge subject performance in general contexts.

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. An AVR onboard 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

An initial experiment tests 40 subjects on 5 DOFs of the right arm, as a proof of concept to determine whether such a system effects people's ability to gain new motor skills, hopefully deepening their understanding and hastening their progress. To test this, we split 40 subjects into two even groups: the first receive visual feedback of tasks they are told to imitate, and the second also receive additional tactile feedback from the vibrotactile actuators described above.

A. Protocol

Subjects are brought into the lab space, with a roughly 10'x20' work-area covered by the Vicon optical tracking system. Each is run through a ten minute calibration routine, to adjust the template models to each specific body. They are then sat down at a desk with a computer screen. All users then have the vibrotactile actuators installed, even if not to be used, so that the suits otherwise feel the same. The typical user setup for experimentation is shown in Fig. 5. Users' elbows remain static on the table, so the shoulder-elbow joint only has the rotational degree of freedom available, for movement simplification.

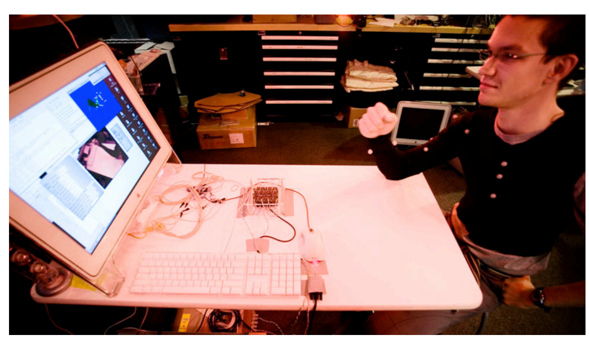

Fig. 5. Typical user setup. The user is sat at the end of a desk, arm placed on the desk to imitate motions, and the opposing computer screen shows still and moving video images for them to imitate.

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 another the 'teacher' holding a still position with their right arm. During that time, the users experience tactile feedback for the first time, and so are given time to get used to the type of feedback, and their influence on it. 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, videos 3-10 seconds in length are shown. To analyze 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 Figs. 6 and 7, respectively.

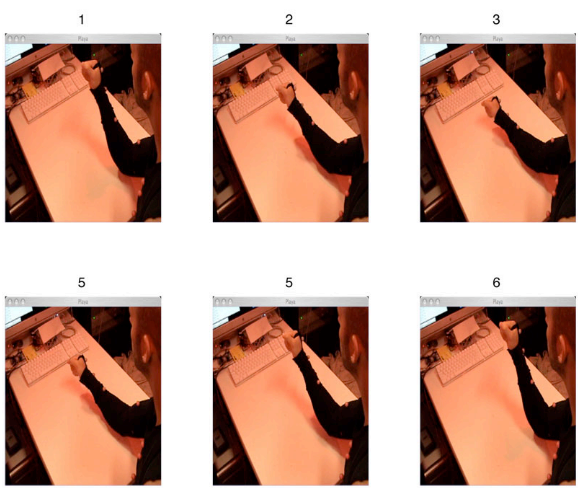

Fig. 6. An image sequence representing 0.5 sec intervals of a simple motor learning video. In this introductory video, only the elbow is moved, and very slowly, enabling subjects to get acquainted to the feedback mechanism of the system. Compare to Fig. 7

After roughly 20 minutes of motion videos are shown with a range of levels of difficulty, the user is disconnected from the system and given a short questionnaire used to assess the usefulness, comfort level, and readability of the vibrotactile system. This is scored on a 1-7 Likert scale from 'strongly disagree' 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 average on the 7 point Likert scale). All users felt they improved their performance over time (5.6/7), but the tactile group noted that this required more conscious effort (5.3/7 vs 4.4/7). No users felt significant fatigue from the experiment, but users with tactile

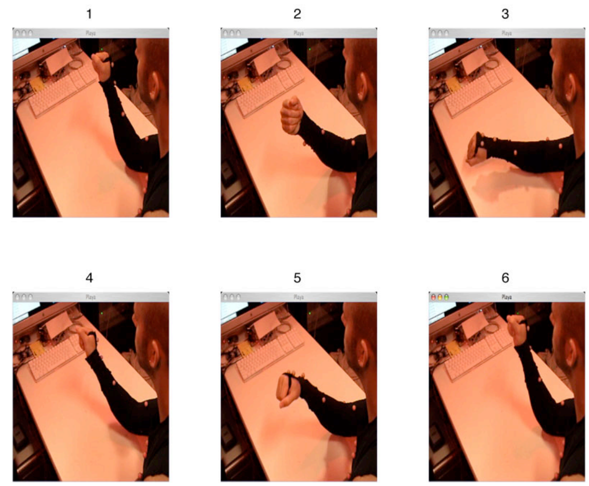

Fig. 7. An image sequence representing 0.5 sec intervals of a difficult motor learning video. In this difficult video, all joints are moved very quickly, enabling subjects the chance to attempt something too difficult for most to adequately mirror. Compare to Fig. 6

feedback (3.7/7) felt more fatigued than the visual feedback alone (2.7/7).

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 (6.2/7), but that the specific method of feedback did not significantly help (4.9/7). They felt strongly that they received joint angle information from the device over time (6.4/7) and joint rotation information, although slightly less so (5.8/7).

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 left 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 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 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,

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

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.

An initial look at frame-by-frame performance data shows that the addition of tactile feedback enhances performance at almost all times, the only exception being the initial moments of a new video, where users react more quickly without tactile feedback. Given the acclimation time, this is to be expected until users have longer to adjust. Subjects utilizing this new feedback had overall a reduction of error, as calculated in Eq. 2, of 21%, statistically very significant ($p = 0.015$).

To further analyze performance, Eq. 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. Fig. 8 shows the relative trial performance of the two groups. Notably, the addition of feedback at all times enhances performance, independent of task difficulty.

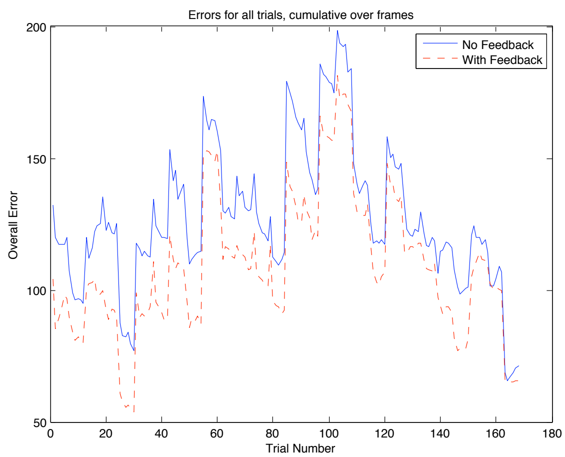

Fig. 8. Measure of errors integrated over a full trial, averaged over all users, errors measured as in Eq. 2. Note that at all times perfomance is improved with the addition of tactile feedback.

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 Eq. 4,

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

where s represents the subjects and m represents the different movies, of total number S and M, respectively.

We now have 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 Eq. 5 using a linear least squares sitting form, the results of which are shown in Fig. 9.

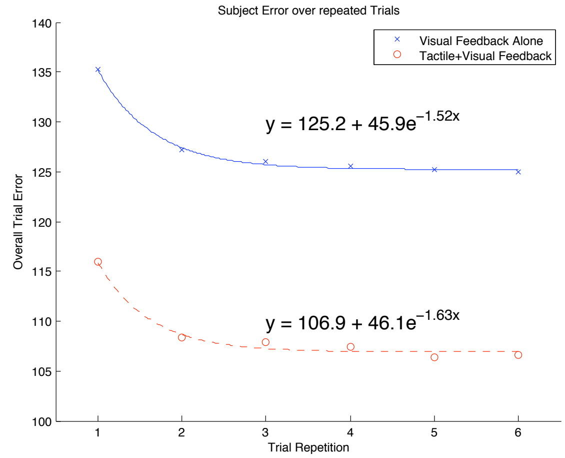

Fig. 9. A measure of subject improvement over the six study trials for each movie. The data is fit to a fading exponential model, as shown. Steady state errors are reduced by 15%, and learning rate is improved by 7%.

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 ($p < 0.01$). Furthermore, improvement did not seem dependent on task difficulty or arm velocity, but stretched across all tasks, as shown graphically in Figure 8.

To sum up, with tactile feedback given on a subsystem of the human body, in a method that users felt was not ideal for them to understand, placing actuators based on hypothesis and giving a linear error type of feedback with no fine tuning, we still noted a statistically very significant gain of 15% in subjects' performance, and accelerated learning of 7%. Given the nature of the experiment (joint number, task difficulty, time to acclimate to the system) and the type feedback given, we can only expect the numbers to improve as we move towards a full-body real-activity system. We have shown only a proof of concept, that in the worst case scenario we still 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 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.

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.

Finally, we do not know how much users can improve with a system like this, over a long amount of time. In a sense, the complexity necessitates that longer times will be necessary to adjust to a full-body suit, but 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. Sports and dance are the most obvious applications for this device. The market for golf swing training alone is already enormous.

Another application for motor learning improvements is neurological rehabilitation, such as post-stroke. 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 need to be done to find out the efficacy of this claim.

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 would allow for static motor learning, so that people can train themselves to sit and stand properly in a much shorter time, like having someone looking over your shoulder and correct your posture at all times, instead of noticing that 10 minutes have gone by while one slouched.

There are many avenues for future research, many possible applications of this type of feedback to our daily lives. Future work must 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 21%; learning rate is improved by 7%; and steady-state learning errors, the measure of performance over time, is improved by 15%. Given the setup we hypothesize that in more complex tests, improvements will increase. Subjects with feedback showed higher level of attention, correcting their motions at times when those without feedback stood idle. Most importantly, this all occurred with users feeling that 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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