Study of finger force variability for physical therapists and untrained subjects

Kanza Khan*, Dingli Qin*, Daniela Glaser*, Alican Nalci*, Catherine Printz†, Carter McElroy† and Pamela Cosman*
*Deptartment of Electrical and Computer Engineering, UC San Diego, La Jolla, CA, 92093-0407
pcosman@eng.ucsd.edu, 858-822-0157
†Deptartment of Rehabilitation Services, UC San Diego Health System

***Abstract*—Physical therapy exercises often involve a patient exerting a force on an object. When a physical therapist shows a patient how much force to exert, the patient may or may not be able to accurately replicate at home what they were shown in the clinic. We study the ability of therapists and of untrained subjects to exert a steady force. Force is measured using a fingertip pressure sensor. We also study the ability to remember and repeat a force value previously maintained. In the absence of real-time visual feedback of achieved force, untrained subjects do less well than physical therapists at holding steady values and at remembering and repeating a previously held value. We introduce a measure of the rapidity of matching success, and find its relation to baseline pressure values.**

***Keywords*—Physical therapy, pressure sensor, force steadiness, force repeatability, pressure feedback.**

I. Introduction

Physical therapy is crucial for rehabilitation following many different types of surgery and injury, but it is often severely hampered by lack of access to physical therapists (PTs) and lack of adherence to home therapy regimens. The compliance rate for home therapy programs can be quite low, due to perceived barriers to exercise, lack of positive feedback, and degree of helplessness [1]–[4]. Home regimens traditionally involve verbal instructions from PTs as well as printed pictures showing exercises. There are some higher-tech systems for home exercise programs which use telemedicine, virtual reality, and robotic programs to promote compliance (e.g., [5]–[8]). Some systems use sensors, either to passively monitor a patients status, provide feedback so an action can be modified, or use actuators to assist the patient in completing a motion (e.g., [9]–[14]). These sensors are usually aimed at capturing motion rather than pressure achieved.

Exercises generally involve motion as well as pressure, but in the current paper we focus only on pressure or force, which is importance in many physical therapy exercises. For example, a patient may grip a ball to regain hand strength, and it would be useful to know the grip strength to monitor progress. As another example, a stroke patient who has lost some function in her arm may be assigned an exercise involving lifting the arm while the PT resists the motion with moderate downward force. At home, the patient's husband will assist by supplying the downward force, but may not achieve the same value as the PT used. If the spouse performs the steps at the clinic under the supervision of the PT, will he be able to remember the force sensation and do the same action at home during the daily exercises needed for rehabilitation?

The long-term goal of this project is to improve physical therapy outcomes with a home-based system that can provide guidance for patients and caregivers (e.g., family members). Since therapy exercises carried out at home are often done incorrectly, providing a guidance system will require being able to quantify what it means to do an exercise correctly. We consider two definitions of what it means to correctly match a target pressure. We first look at how well experienced PTs can accomplish a task, such as squeezing a stress puck, which they might assign to a patient or caregiver. The task involves holding a steady force (steadiness) or achieving a certain specified level of force (repeatability), and a PT in normal practice (without information on force fed back) has some level of variability in doing the task. If a home-based guidance system can allow untrained patients and their caregivers to replicate forces during exercises as well as a PT can during normal practice in a clinic, then that home-based exercise can be considered to be done correctly.

Another definition of matching a target pressure correctly could be taken as achieving a pressure $P(t)$ as a function of time that remains within some tolerance band $[P_T - \delta, P_T + \delta]$ around the target value P_T for some duration of time T_D, where δ is the maximum deviation from the target value that is considered acceptable for a match. With this definition of pressure match success, the time-to-success, T_S, could be defined to be the first time at which the achieved pressure $P(t)$ is within the tolerance band $[P_T - \delta, P_T + \delta]$ and remains within it for the specified duration T_D. Using a definition of this type requires choosing values for δ and T_D. If δ is large and T_D is short, achieving the pressure match might be trivially easy, whereas if δ is chosen too small and T_D is long, achieving the pressure match might be impossibly difficult. We examine how to choose these parameters and how they relate to the target pressure P_T.

There has been considerable prior work on force steadiness during production of a constant force, for example with fingers, arms and legs (e.g., [15]–[17]). There has also been prior work on force repeatability (e.g., [18]–[20]). Our work differs from the previous work in three main respects, all of which stem from our application domain of physical therapy assistive technology. First, we make a comparison between physical therapists and untrained subjects with regard to force steadiness and repeatability. Second, prior work on force repeatability generally focussed on repetitions of maximal voluntary force, or else provided subjects with visual feedback in order to achieve a sub-maximal target force, and the issue of repeatability therefore did not pertain to whether subjects could remember and repeat a sub-maximal force level, but rather had to do with, for example, whether EMG variables were repeatable, or whether a pattern of fatigue could be found during the repetitions. In contrast, our concept of repeatability for the home physical therapy application has to do with whether subjects can remember and repeat some moderate force level that they were instructed to achieve. Lastly, we introduce the time-to-success measure, which captures how rapidly the target force is achieved to within a specified accuracy. This measure may have value for comparing assistive technologies. For example, since physical therapy exercises are often done by older adults who are not used to computer interfaces, different graphical user interfaces might be compared on the basis of how easily and rapidly they allow patients to achieve correct values in their exercises.

This paper is organized as follows. In Section II we describe the experimental setup and the quantities of interest. We examine how steadily PTs as well as untrained adults can hold a force (steadiness), and how well they can remember a previous force value and achieve the same value again (repeatability). The untrained subjects are also tested with real-time visual feedback of the achieved force. In Section III we provide the experimental results on repeatability and steadiness. In Section IV we look at relationships among δ, T_D, and P_T. Conclusions are in Section V.

II. Experimental Methods

A. Experimental Setup

The fingerTPS system (Pressure Profile Systems, Inc., Los Angeles, CA) can collect pressure data from individual fingertip sensors as well as a palm sensor. In our experiments, we used a single fingertip sensor on the index finger of the dominant hand. With the forearm resting on a table, seated subjects placed the index finger on a marked spot on a squishable stress puck (see Fig. 1).

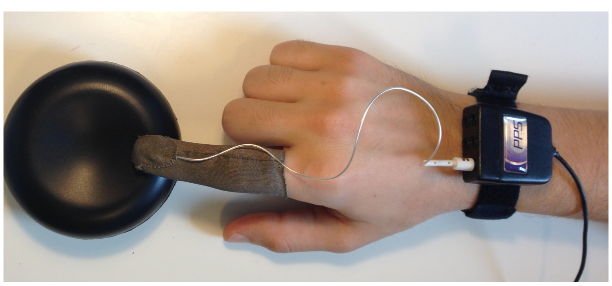

Fig. 1. Test subjects wear a sensor on the index finger and push down on a stress puck

The fingerTPS sensors return data on force, not pressure. The force data can be converted to pressure by determining the active area of the sensing pad which is used in any given application. In our case, because the positions of the finger and stress puck were kept uniform throughout the experiment for all test subjects, the conversion factor does not vary, so we use the terms force and pressure interchangeably.

During the first portion of the experiment, which we refer to as self-matching trials, subjects were not given any visual feedback on their achieved force. Subjects were asked to push down with a "light" pressure and hold it steady for 30 seconds. Then they took their finger off the stress puck, waited a few seconds, and did it again (for a total of five times). While the first one was arbitrarily chosen, in the remaining four, the subject was instructed to try to remember and match the pressure they used before. After a short break, subjects were instructed to choose a "medium" pressure (with five repetitions) and then finally a "heavy' pressure. Fig. 2 shows an example of the raw data for two subjects for the self-matching trials. The x-axis shows time ranging from 0 to 30 seconds, and the y-axis is the sensor output. One subject shows much less variability over repetitions than does the other.

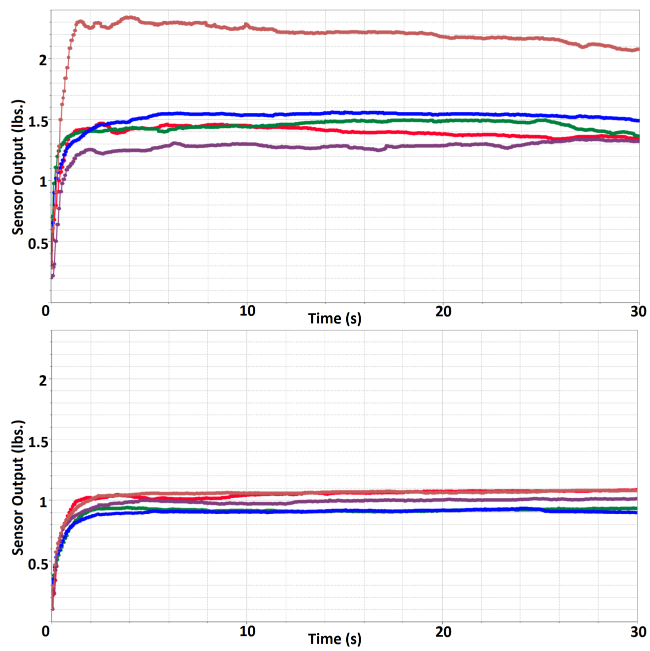

Fig. 2. Pressure vs. time for two subjects trying to repeat a "medium" pressure

In the second portion of the experiment, subjects were given real-time visual feedback on the achieved pressure. Subjects were given two minutes of training to learn how to use the feedback. In the simple graphical user interface (GUI), a fixed horizontal line shows the target pressure, and the pressure bar moves up and down with pressure achieved (Fig. 3). The user tries to push down so as to make the pressure bar reach the horizontal line. The rectangle on the right is a zoomed-in view of the first one, so it allows for fine adjustment. Subjects were given three pressure target values: 0.5, 1.0, and 1.5 pounds, corresponding to light, medium, and heavy pressure. Fig. 4 shows an example of the pressure vs. time data for two subjects using the feedback system.

B. Quantities of Interest

For both self-matching trials and feedback trials, the data from the first 10 seconds is ignored, as this is considered a stabilization period. In the following, values are calculated for the data from 10 to 30 seconds. For a given subject, let $P_i(t)$ denote the sensor output value as a function of time, on the ith repetition of a given trial, $i = 1, 2, 3, 4, 5$.

Let M_i, for $i = 1, 2, 3, 4, 5$, denote the average value of $P_i(t)$ over the time interval from 10 to 30 seconds. Let M

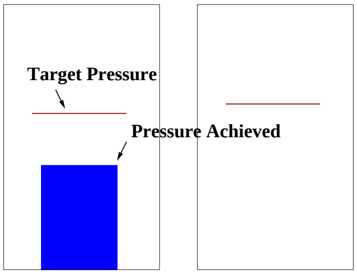

Fig. 3. The GUI provides feedback on the pressure achieved.

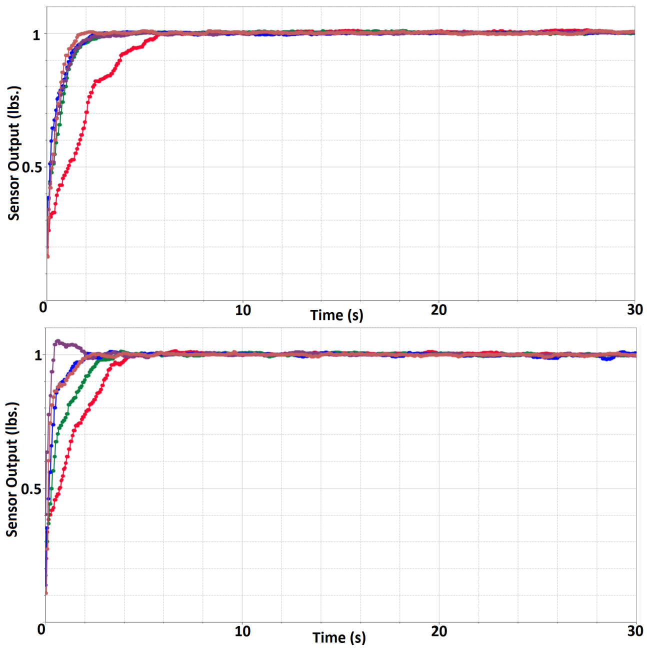

Fig. 4. Pressure vs. time given feedback.

denote the mean of the five M_i values. The degree to which the five M_i values differ from one another is an indication of how well a subject is able to remember and repeat the same average value. Our measure of repeatability, R, is taken to be the variance of these five mean values.

Let V_i denote the variance of $P_i(t)$ over time, for $i = 1, 2, 3, 4, 5$. Then V_i is an indication of how steadily (constant over time) a person can hold a given pressure value. We compute the average value of the five V_i values as our measure of steadiness, S.

C. Limitations of Data Collection

There are two limitations to accuracy in our data acquisition. First, the fingerTPS sensors are designed primarily for short duration testing, and when subjected to a prolonged load, the pressure or force starts to creep up. The creep is relatively small, roughly one tenth of one percent per second, so we neglected it. Second, because of difficulties of integrating the fingerTPS calibration device with our GUI for providing real-time visual feedback, the sensor was not calibrated separately for each user. However, we are not concerned with absolute values of pressure or force, but rather with repeatability R and steadiness S. Since both of these measures involve computing variances, any constant offset term that might be present in the data would disappear in the computation of the variance.

III. Experimental Results

Twenty adults not trained in physical therapy were used as test subjects, providing data for both the self-matching and feedback trials. In addition, six experienced PTs provided data for self-matching trials.

Fig. 5 shows a scatter plot in which repeatability R is plotted vs. the mean achieved value M for the self-matching trials. For each of the 20 untrained subjects, there are 3 plotted points shown as x's, corresponding to the self-selected light, medium, and heavy pressures. The corresponding points for the PTs are shown as circles. An ideal value of the R metric would be zero, meaning that a subject achieves exactly the same mean value as before. On average, the PTs score better on repeatability than untrained subjects (1.61×10^{-2} vs. 2.64×10^{-2}). Comparing worst case performance, there are 7 x's (corresponding to untrained subjects) with higher values (worse repeatability) than the highest of the circles (corresponding to PTs).

Fig. 6 is the corresponding scatter plot for repeatability for the feedback trials. Note that the PTs did not use the feedback system, so the circle markers for the PT data are copied from Fig. 5. Even with this expanded vertical scale, the 60 x markers fall on top of each other in three groups at x-values of 0.5, 1.0, and 1.5 and y-value nearly zero. As expected, all the untrained subjects with feedback do much better on repeatability than they did in the absence of feedback. Also, they do much better than all the PTs (when the PTs do not have feedback).

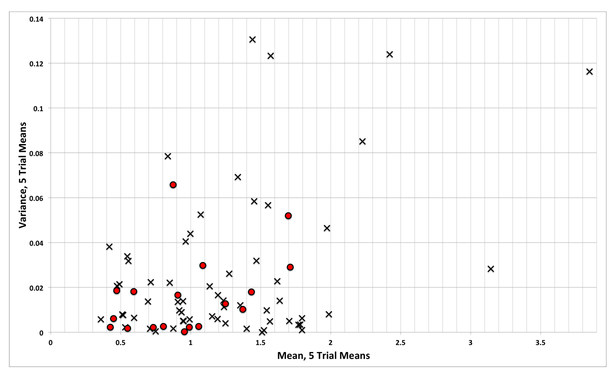

Fig. 5. Repeatability scores for untrained subjects and PTs, no feedback.

Fig. 7 shows a scatter plot in which steadiness S is plotted vs. the mean achieved value M for the self-matching trials. As before, for each of the 20 untrained subjects, there are 3 plotted points corresponding to the self-selected light, medium, and heavy pressures. PT values are shown as circles. An ideal value of the S metric would be zero, corresponding to perfectly steady pressure over time. The PTs on the average score better on steadiness than untrained subjects (4.40×10^{-4} vs. 17.2×10^{-4}). Comparing worst case performance, there are 18 x's (corresponding to untrained subjects) with higher values (worse steadiness) than the highest of the circles (corresponding to PTs). Fig. 8 is the corresponding scatter plot for steadiness for the feedback trials (PT data are copied from Fig 7). As expected, all of the untrained subjects with feedback

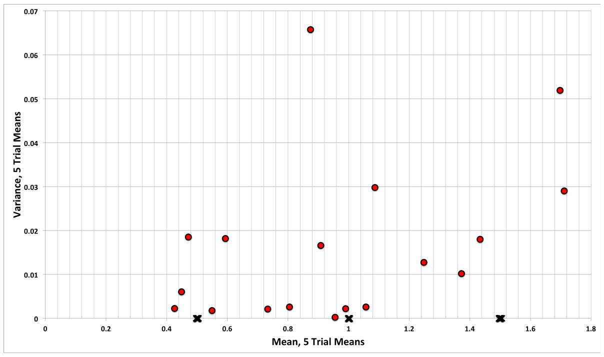

Fig. 6. Repeatability scores for untrained subjects (with feedback) and PTs (without feedback).

do better on the steadiness measure than they did without it. Also, most, but not all, of the untrained subjects do better on steadiness than the PTs when the untrained subjects have feedback and the PTs do not.

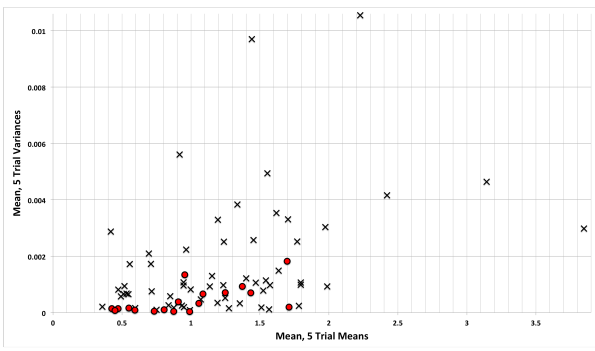

Fig. 7. Steadiness scores for untrained subjects and PTs, no feedback.

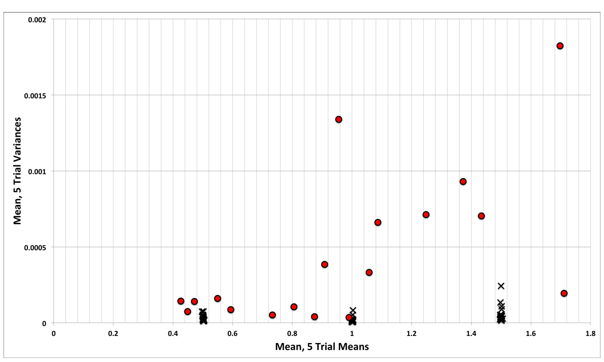

Fig. 8. Steadiness scores for untrained subjects (with feedback) and PTs (without feedback).

IV. Time-to-success

As discussed in the introduction, matching pressure correctly could be defined as producing a pressure $P(t)$ as a function of time that remains within some tolerance band $[P_T - \delta, P_T + \delta]$ around the target value P_T for some duration of time T_D. The time-to-success, T_S, is defined to be the first time at which the achieved pressure $P(t)$ is within the tolerance band $[P_T - \delta, P_T + \delta]$ and remains within it for the specified duration T_D. These quantities are illustrated in Fig. 9. The solid horizontal line is the target pressure, and the dashed horizontal lines above and below it are the upper and lower limits of the tolerance band. The achieved pressure $P(t)$ first crosses into the tolerance band at time T_1, but since it does not remain within the band for duration T_D, T_1 cannot be considered the time-to-success. Time T_S is the first time at which the achieved pressure crosses into the tolerance band and stays within the band for duration T_D.

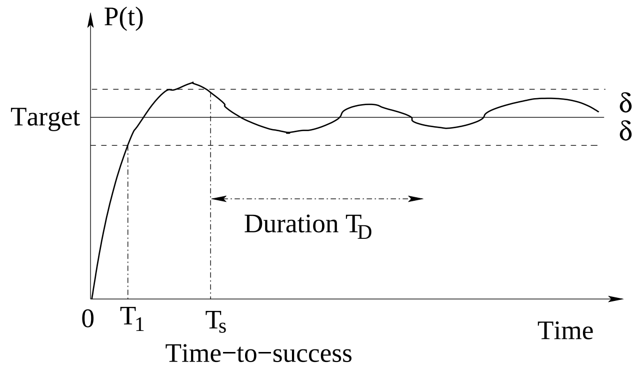

Fig. 9. Illustration of $P(t)$ with target pressure, T_D, δ, and time-to-success T_S.

Using this definition, the time-to-success can be computed for various values of δ and T_D from a single data trace of $P(t)$ for a subject. The type of result one obtains from this is shown in Fig. 10, which shows the time-to-success on the y-axis versus the tolerance band width on the x-axis, where T_D was set to 0.5 seconds. The curve has the general shape one would expect. First, the curve is non-increasing, because as one increases the tolerance band width, this can only have the effect of making success easier; success cannot be achieved later with a larger δ than with a smaller δ. The curve flattens out at the right, because at a certain point the task is easy to accomplish, and then making the task even easier (tolerance band even wider) has little effect. On the left hand side, the curve goes up sharply, because when δ is too small, the task is impossible; the subject cannot hold the pressure steady enough to remain within the tolerance band.

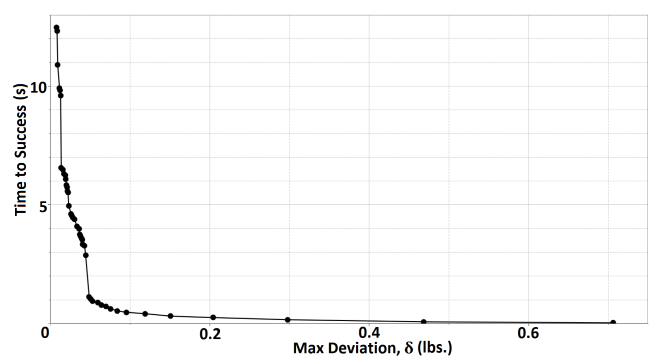

Fig. 10. Example of time-to-success vs. tolerance band width.

If we view the behavior on the left side as being where the task of pressure matching for the given (δ, T_D) is too hard, and the behavior on the right side is where the task is too easy, the plot appears to have a knee point where the task transitions from too hard to too easy. We use the function knee_pt.m in Matlab to find the knee points for curves of this type. Fig. 11 shows how the δ values at the knee points depend on target pressure P_T and duration of match T_D.

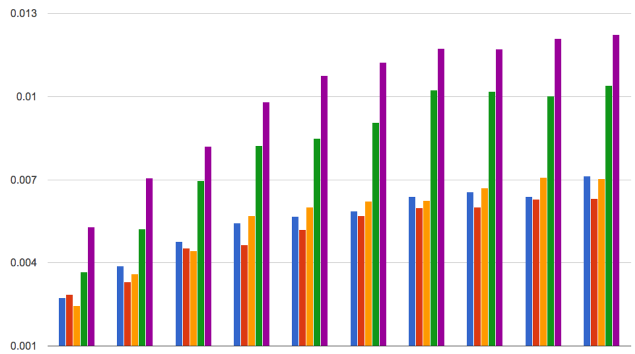

Fig. 11. Y-axis shows tolerance band widths at the knee points of the time-to-success vs. δ curves. X-axis has 5 different values of pressure for 10 different values of time duration.

The data were taken from one subject using the feedback system, with 10 repetitions at each value of target pressure (average values are computed over the 10 repetitions). The x-axis shows 10 separate groups of bars, where each group has 5 bars. The 10 groups correspond to match durations T_D of 1 to 10 seconds. Within each group, the 5 bars correspond to 5 values of target pressure (0.5, 0.75, 1.0, 1.25, 1.5 pounds) increasing from left to right. The y-axis indicates the δ value at the knee point of the curve. Given the calibration issues, numeric values may be inaccurate, but the trends shown in the figure are of interest. Within each of the 10 groups, there is a generally increasing trend, indicating that for higher values of target pressure, the δ at the knee point is larger. A person needs a wider tolerance band to accomplish the task when the target pressure is higher. The trend does not hold for the very lightest pressures, suggesting that when people try to maintain a very light pressure, they find it hard to do so steadily. Previous studies on force steadiness such as [15], [21], found that steadiness as measured by the coefficient of variation (CV) had a U-shape, with intermediate force levels producing the steadiest results. Our results for time-to-success are consistent with this prior work on CV.

Looking across the 10 groups, there is a generally increasing trend, showing that the knee point is occurring at higher values of the tolerance band when the duration required for a match is increased. But there is a saturation effect as one moves to the right, because when the duration of the match becomes fairly long (say, 5 or 6 sec), then making it somewhat longer does not make the task noticeably harder, and the knee point of the curve does not move much towards larger tolerance bands.

Time-to-success measures may be useful for comparing different guidance systems. For example, the current GUI has two pressure bars, presented with certain colors, line widths, etc. In making changes to the GUI (e.g., to simplify it and adapt it for use by older adults), the time-to-success measure may offer a framework for comparing one version of the system against another, since it indicates how quickly and easily the feedback system helps a person to achieve the target.

V. Conclusions and Future Work

The contributions of this paper are as follows: (1) We examine repeatability in the context of remembering and repeating previous force values, and we introduce the measure of time-to-success. The repeatability measure may be useful in a physical therapy application, since the patient and therapist would like to know whether the patient is achieving the assigned pressure level. The time-to-success measure may be useful for comparing different types of visual feedback, to see whether one system is better than another in allowing patients to quickly and easily achieve their target. (2) We compared PTs and untrained subjects, and found that without feedback, many subjects do worse than the most variable PT on repeating an average target pressure, and on holding a pressure steadily. For repeatability, simple visual feedback helps untrained subjects achieve the average target force very accurately, better than any subject (trained or untrained) who does not have feedback. For steadiness, the feedback causes substantial improvement as well, although several of the PTs without feedback were steadier than some untrained subjects with feedback. (3) The time-to-success measure showed that when the target pressure to be matched is higher, a person needs a wider tolerance band to accomplish the task, consistent with related measures in the literature.

Our long-term goal is to provide feedback to allow home-based exercises to be done as accurately at home as they would be done in a physical therapy clinic, but one could argue that there is no need to be more accurate than what is done in the clinic. The results show that for the simplified task in this study, the feedback based on the fingerTPS sensor allows the task of repeating an average assigned force to be accomplished more accurately than is done by physical therapists. This margin is important because it suggests that we may be able to still guide patients to achieve target pressures accurately even if we significantly degrade the sensor accuracy being fed back. In future work, beyond overcoming the data accuracy limitations mentioned in Section II-C, we intend to explore basing the visual feedback on an inexpensive Kinect sensor, rather than the fingerTPS sensors which are considerably more expensive. This means that the depth of the indentation would be fed back, rather than the actual achieved pressure. Given the wide margin by which steadiness and repeatability in the presence of pressure feedback are improved compared to the case of no feedback, it may be that even inaccurate feedback based on depth measurements may be sufficient to achieve therapy exercise force correctness comparable to that achieved in the clinic.

References

[1] K. Jack, S. M. McLean, J. K. Moffett, and E. Gardiner, "Barriers to treatment adherence in physiotherapy outpatient clinics: a systematic review," *Manual Therapy*, vol. 15, no. 3, pp. 220–228, 2010.

[2] S. M. McLean, M. Burton, L. Bradley, and C. Littlewood, "Interventions for enhancing adherence with physiotherapy: A systematic review," *Manual Therapy*, vol. 15, no. 6, pp. 514–521, 2010.

[3] L. Yardley, M. Donovan-Hall, K. Francis, and C. Todd, "Attitudes and beliefs that predict older people's intention to undertake strength and balance training," *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, vol. 62, no. 2, pp. P119–P125, 2007.

[4] J. Miller, A. Litva, and M. Gabbay, "Motivating patients with shoulder and back pain to self-care: can a videotape of exercise support physiotherapy?" *Physiotherapy*, vol. 95, no. 1, pp. 29–35, 2009.

[5] P. V. Mhatre, I. Vilares, S. M. Stibb, M. V. Albert, P. Laura Pickering, C. M. Marciniak, K. Kording, and S. Toledo, "Wii fit balance board playing improves balance and gait in Parkinson disease," *PM&R*, 2013.

[6] V. Fung, A. Ho, J. Shaffer, E. Chung, and M. Gomez, "Use of Nintendo wii fit in the rehabilitation of outpatients following total knee replacement: a preliminary randomised controlled trial," *Physiotherapy*, 2012.

[7] J. E. Deutsch, J. A. Lewis, and G. Burdea, "Technical and patient performance using a virtual reality-integrated telerehabilitation system: preliminary finding," *IEEE Trans. Neural Systems and Rehabilitation Engineering*, vol. 15, no. 1, pp. 30–35, 2007.

[8] E. J. Lyons and C. Hatkevich, "Prevalence of behavior changing strategies in fitness video games: Theory-based content analysis," *J. of Medical Internet Research*, vol. 15, no. 5, 2013.

[9] S. Bamberg, A. Y. Benbasat, D. M. Scarborough, D. E. Krebs, and J. A. Paradiso, "Gait analysis using a shoe-integrated wireless sensor system," *IEEE Trans. on Info. Tech. in Biomedicine*, vol. 12, no. 4, pp. 413–423, 2008.

[10] J. A. Paradiso, S. J. Morris, A. Y. Benbasat, and E. Asmussen, "Interactive therapy with instrumented footwear," in *CHI'04 Extended Abstracts on Human Factors in Computing Systems*. ACM, 2004, pp. 1341–1343.

[11] R. W. Lindeman, Y. Yanagida, K. Hosaka, and S. Abe, "The tactapack: A wireless sensor/actuator package for physical therapy applications," in *14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, IEEE, 2006, pp. 337–341.

[12] K. N. Adnan, I. Ahmad, M. Coussens, A. Eliakim, S. Gallitto, D. Grochow, R. Koeppel, D. Nemet, J. Rich, F. Waffarn *et al.*, "A haptic simulator for training the application of range of motion exercise to premature infants," *J. Medical Devices*, vol. 3, no. 4, 2009.

[13] R. Secoli, M.-H. Milot, G. Rosati, D. J. Reinkensmeyer *et al.*, "Effect of visual distraction and auditory feedback on patient effort during robot-assisted movement training after stroke," *J NeuroEng Rehabil*, vol. 8, no. 1, pp. 21–30, 2011.

[14] P. S. Lum, D. J. Reinkensmeyer, and S. L. Lehman, "Robotic assist devices for bimanual physical therapy: preliminary experiments," *IEEE Trans. Rehabilitation Engineering*, vol. 1, no. 3, pp. 185–191, 1993.

[15] F. Danion and C. Gallea, "The relation between force magnitude, force steadiness, and muscle co-contraction in the thumb during precision grip," *Neuroscience Letters*, 368, pp. 176–180, 2014.

[16] O. Missenard, D. Motte, and S. Perrey, "Factors responsible for force steadiness impairment with fatigue," *Muscle & Nerve*, pp. 1019–1032, December 2009.

[17] R. Krupenevich, N. Murray, P.M. Rider, Z.J. Domire, and P. DeVita, "The relationship between muscle force steadiness and visual steadiness in young and old adults," *Motor Control*, 2014.

[18] A. Rainoldi, G. Galardi, L. Maderna, G. Comi, L. Lo Conte, and R. Merletti, "Repeatability of surface EMG variables during voluntary isometric contractions of the biceps brachii muscle," *J. of Electromyography and Kinesiology*, 9, pp. 105–119, 1999.

[19] A. Rainoldi, J.E. Bullock-Saxton, F. Cavarretta, and N. Hogan, "Repeatability of maximal voluntary force and of surface EMG variables during voluntary isometric contraction of quadriceps muscles in healthy subjects," *J. of Electromyography and Kinesiology*, 11, pp. 425–438, 2001.

[20] A. Jastrzebska and R. Blacha, "Effect of exhaustive incremental treadmill effort on force generation repeatability in biathletes," *Journal of Motor Behavior*, Vol. 46, No. 4, 2014.

[21] A.B. Slifkin and K.M. Newell, "Noise, information transmission, and force variability," *J. Exp. Psych.* 25, pp. 1–15, 1999.