Assessment of Haptic Interaction for Home-Based Physical Tele-Therapy using Wearable Devices and Depth Sensors

Angelos BARMPOUTIS [a,1], Jose ALZATE [b], Samantha BEEKHUIZEN [c],
Horacio DELGADO [d], Preston DONALDSON [c], Andrew HALL [b], Charlie LAGO [c],
Kevin VIDAL [c] and Emily J. FOX [e,2]

[a] *Digital Worlds Institute, University of Florida, U.S.A.*
[b] *Department of Electrical Engineering, University of Florida, U.S.A*
[c] *Department of Biomedical Engineering, University of Florida, U.S.A*
[d] *Computer and Information Science and Engineering, University of Florida, U.S.A*
[e] *Department of Physical Therapy, University of Florida, U.S.A*

Abstract. In this paper a prototype system is presented for home-based physical tele-therapy using a wearable device for haptic feedback. The haptic feedback is generated as a sequence of vibratory cues from 8 vibrator motors equally spaced along an elastic wearable band. The motors guide the patients' movement as they perform a prescribed exercise routine in a way that replaces the physical therapists' haptic guidance in an unsupervised or remotely supervised home-based therapy session. A pilot study of 25 human subjects was performed that focused on: a) testing the capability of the system to guide the users in arbitrary motion paths in the space and b) comparing the motion of the users during typical physical therapy exercises with and without haptic-based guidance. The results demonstrate the efficacy of the proposed system.

Keywords. Haptics, Human-Computer Interaction, Tele-Health, Physical Therapy, Kinect

1. Introduction

National statistics from the United States [1] indicate that increased life expectancy in recent decades has contributed to the aging of the population [2]. The aging population as a whole and growth of the very oldest segments within it are associated with the transition from informal to formal home health care (HHC) delivery [2]. In 2007, more

than 1.4 million men and women received HHC each day and Physical therapy (PT) is the second commonly used type of HHC service [3].

The aforementioned facts clearly demonstrated the significance of home health research, especially when it focuses on the enhancement of the traditional types of delivery using new technologies from the emerging fields of tele-therapy and tele-health. One of the more challenging issues in tele-health is the lack of physical contact between the patient and the health care provider. Physical contact is required in many forms of health care to primarily assist in the physical examination of the patient, and secondarily, to facilitate direct communication with the patient. There are, however, several types of home-based therapies that do not require physical presence of the care provider and therefore such services could be offered in the form of home-based tele-care with haptic feedback. The current state-of-the-art in home tele-health combines several telecommunication technologies as well as sensing technologies for monitoring the environment and other medical devices for home use [4]. The use of haptic-based tele-health technologies, however, has not been well studied and applied to PT since the development of haptic technologies is still a growing area of research.

Arm sleeves with haptic feedback for patients that have suffered a stroke and have lost the ability to perform basic motor functions were presented in [5,6]. A more recent extension of this project included a prototype compression sleeve lined with vibration motors that are controlled using a body tracking method based on Microsoft Kinect sensor. Depth sensor-based body tracking has been used in other areas of rehabilitation [7], including game-based rehabilitation systems that were presented in [8].

In addition, several exoskeletal systems with haptic feedback have been presented in literature. A robotic exoskeleton driven by brain-computer interface for rehabilitation therapy was presented in [9]. An active vision system, through the combination of Microsoft's Kinect infrared 3D depth analysis and an eye-tracking system, can indicate a patient's intention to move the affected limb, and will feed the information continuously into the BCI classifier that generated real-time feedback of the robotic exoskeleton. Several other exoskeletal systems for therapy have been proposed and applied to various types of rehabilitation [10,11,12,13,14].

This paper presents a prototype system that aims to overcome the limitations of the current HCC PT methods by introducing a new technological framework for home-based physical tele-therapy. More specifically, in the case of HHC PT, one way to increase overall opportunities for practice and amount of practice is to increase the number of sessions or times per week that a therapist works with a patient. Every session of therapy, however, does not require hands-on one-on-one care. While this is needed for some patients with severe functional deficits, this is often not the case. In fact, most patients need basic guidance to simply complete a basic exercise routine. The proposed prototype system aims to overcome the aforementioned limitation of PT dosage by introducing a novel, cost-effective framework for HHC PT. This framework aims to enhance the traditional HHC practices by providing assistive mechanism that will track the patients using the Kinect sensor, and guide them using a wearable haptic device that generates vibratory cues. In the following sections, a pilot study with 25 human subjects is presented that assesses the efficacy of the proposed haptic interaction for home-based physical tele-therapy. The proposed system could potentially allow therapists to provide services to more patients and also a greater number of therapy sessions by using novel tele-health technologies with haptic feedback.
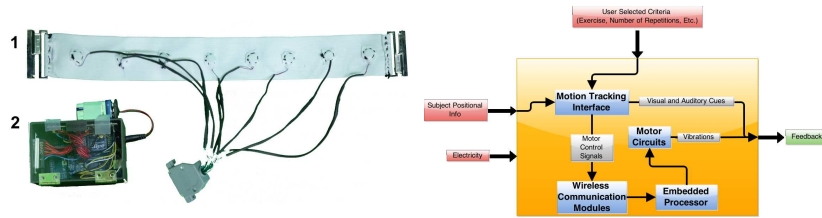
Figure 1. Left: The prototype wearable haptic band with 8 equally spaced motors shown on panel 1 and the wireless communication unit on panel 2. Right: Diagram of the major components of the prototype system.

Figure 2. Test subjects following random vibratory cue-guided trajectories (left), and guided hip abduction exercises (right). The overall experimental setup is also shown, including the virtual training environments.

2. Methods

A prototype system was developed in this project that consists of: 1) a wearable device for haptic feedback, 2) a marker-less motion sensor for tracking the body movements of the users, and 3) a computer with software for triggering in real-time vibratory cues based on the body activity of the user.

The wearable device was in the form of an elastic band with an array of 8 vibration motors that were equally spaced along the band Fig. 1(top left). The purpose of this band was to be worn around a limb, for instance around the thigh, in order the user to be able to feel vibratory cues from 8 discrete directions around the limb. Since each of the motors corresponds to a different location along the band, its vibratory cue can be directly related to directional information. For example a vibration on the front of the leg prompts a forward motion, while a vibration on the back of the leg prompts a backward motion, etc. The vibration motors were controlled wirelessly by a desktop computer through a battery powered Arduino chip with an xBee WiFi receiver attached to the elastic band.

The user body activity was monitored by a Microsoft Kinect sensor (Xbox One model) through a custom-build software using the Java for Kinect (J4K) library introduced in [15]. Several exercise routines were programmed as a sequence of multiple steps, each of the prompted by a vibratory cue towards a specific direction. For example a typical hip abduction exercise is a sequence of outward and inward motion of one leg while standing on the other. It should be noted that these programmed routines are not time-based sequences but interactive processes. The systems monitors the motion of the user, and triggers the next vibratory cue only when the user has performed the previously prompted motion. In the case of hip abduction a predefined range of motion (such as 45degrees) can be used in order to guide the user within the corresponding two extrema of the motion path in this exercise. Similarly, therapist-driven exercises could be
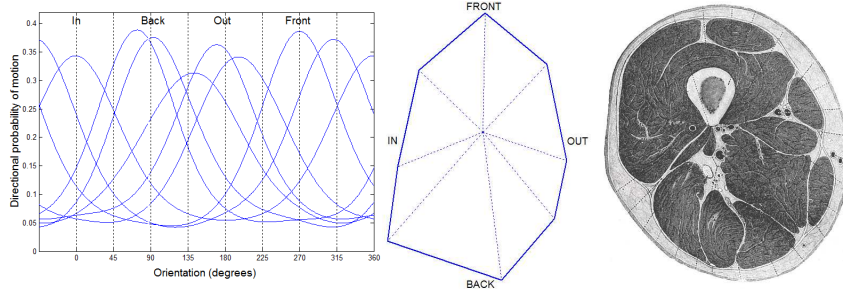
Figure 3. Directional probability of motions triggered by each vibration motor (dashed lines indicate the locations of the motors). The corresponding reconstructed section of the thigh is shown in the middle. An illustration of a thigh section from H. Gray's Anatomy of the Human Body (1858) is shown on the right.

performed in a tele-therapy setting. The following section presents the results of a pilot study that was designed to assess the proposed wearable haptic system.

3. Experimental Results

In order to test and quantitatively evaluate the proposed haptic-driven physical tele-therapy system, we performed two sets of experiments that focus on: a) testing the capability of the system to guide the users in arbitrary motion paths in the 3D space and b) comparing the motion of the users during typical physical therapy exercises with and without haptic-based guidance. For the purposes of this pilot user study we recruited 25 healthy volunteers (age range: 19-45, gender: 60% female) who used the prototype wearable device and participated in the experiments as follows. The users wore the haptic band around their left thigh as shown in Fig. 2 and stood within the field of view of the Microsoft Kinect sensor that was tracking their skeleton in real time (30 fps) using a 25-joint skeletal model. The users also had in front of them a computer monitor showing a mirrored image of them within a virtual training environment.

First, the system generated a random sequence of vibratory cues that were prompting movement towards random directions, which corresponded to the location of the triggered motor around the band (i.e. vibration of the front motor indicated a forward motion, vibration of the external side motor indicated an outward motion, etc.). Each vibratory cue in the random sequence lasted for 1 sec and followed by 1 sec pause. In order to enhance the intensity of the vibratory cues, three adjacent motors were simultaneously triggered each time allowing the users to feel the haptic feedback over their regular clothing. The direction of the user's motion after each vibratory cue was captured using the Kinect sensor, and was used to calculate the directional probability of motions triggered by each motor as a mixture of von Mises distributions as follows:

$$p(x) = \frac{1}{N} \sum_{i=1}^{N} \frac{e^{\kappa \cos(x-d_i)}}{2\pi I_0(\kappa)} \tag{1}$$

where d_i is the user's motion direction after the ith cue ($i \in [1 \dots N]$), $I_0(\kappa)$ is the modified Bessel function of 0th order, and κ was set to 1. Note that $\int_0^{2\pi} p(x)dx = 1$.

Figure 3(left) shows the plots of the calculated probabilities (one for each motor). Under the assumptions that a) the motors are equally spaced and b) the band is wrapped

Table 1. Interaction statistics from the hip abduction experiments

Index	Mean	Std. Deviation
Motion range without haptics	47.5284 deg.	14.2838 deg.
Motion range with haptics	46.3341 deg.	7.6146 deg.
Response time in seconds	0.4073 sec. (12.2178 frames)	0.2258 sec. (6.7732 frames)

around a perfectly cylindrical limb, it is expected that the directional probability of each motor will have a peak at the location of the motor shown as dashed lines in Fig. 3(left). Although this is the case for several motors such as the front, back, and inside motor, others' maximum probability appeared shifted. This indicates that parts of the user motion paths deviated from the desired goal, which could be due to various factors including body tracking errors from the Kinect sensor, non cylindrical shape of the thigh, clothing-related noise and others. Using the estimated peaks from Fig.3(left) and assuming equally spaced motors, the shape of the cross section of the thigh could be approximated using any energy minimization technique Fig.3(center). By observing the approximated section, it is evident that its elliptical shape resembles the shape of a typical thigh as shown in Fig.3(right). In practice, the process of this experiment could be used as a calibration step in order to generate user-specific cues that lead to more precise motion paths.

Furthermore, the test subjects were instructed to perform hip abduction exercises with and without haptic guidance. A comparison of the corresponding motion patterns from a randomly chosen participant is shown in Fig. 4. Both sequences begin with the standing position followed by 10 repetitions of the exercise. By comparing the two motion patterns it is evident that without the haptic guidance the range of motion varies significantly more. This is also reflected in Table 1, which shows a 47% reduction in the standard deviation of the range of motion in the case of haptic guidance. This conclusively demonstrates that the wearable haptic device helped the subjects to have more consistent movement pattern during their exercises, which is a significant factor in physical therapy as this technique can reduce or eliminate deviations from the target motion that the patients may develop over time.

Table 1 also reports the mean (across all subjects) and standard deviation of the range of motion and the interaction response time. The response time was measured as the time between the triggering of a vibratory cue (denoted by dashed lines in Fig. 4) and the change of direction in user's leg motion (shown as local extrema in red circles). Although the reported average response time is 407.3 milliseconds, the response time dropped to 332.7 milliseconds towards the end of the 10 hip abductions, which corresponds to a 21.43% decrease since the beginning of the exercise.

The results of this pilot study demonstrate that the proposed system can be used as a haptic-based guide during physical therapy exercises. In our future studies, the cues could be triggered either by a computer or by a remote therapist in a home-based tele-therapy session. Finally, usability studies will be performed using subjects who have recently experienced HHC PT sessions as well as therapists in order to assess the proposed system in realistic HHC tele-PT scenarios.
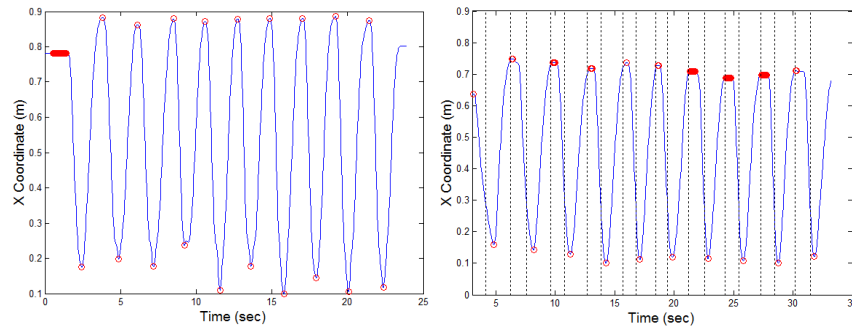
Figure 4. Comparison of the motion pattern during a hip abduction exercise without (left) and with (right) haptic guidance. The dashed lines indicate the timing of vibratory cues and the red circles show local extrema.

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