Virtual Therapist: A Phantom Robot-Based Haptic System for Personalized Post-Surgery Finger Rehabilitation

Zhe Xu, Rebecca Fiebrink, and Yoky Matsuoka

***Abstract*—Finger rehabilitation is crucial to a patient's full recovery following finger surgery. In order to avoid contact-induced infection while simultaneously improving patient motivation and reducing barriers to therapist customization of the rehabilitation system, we design the Virtual Therapist: a Phantom robot-based haptic system with a user-friendly software interface. An anatomically correct finger model is derived and implemented for calculating the four joint angles of a patient's index finger so that only the fingertip needs to be coupled with the Phantom robot for data collection purposes. A demonstration-based user interface allows the therapist to personalize a rehabilitation plan for the patient. We qualitatively validate the efficacy of our proof-of-concept system through observing the performance of three human adults. In less than eight minutes, all three subjects could correctly and proficiently use the system in the role of either patient or therapist.**

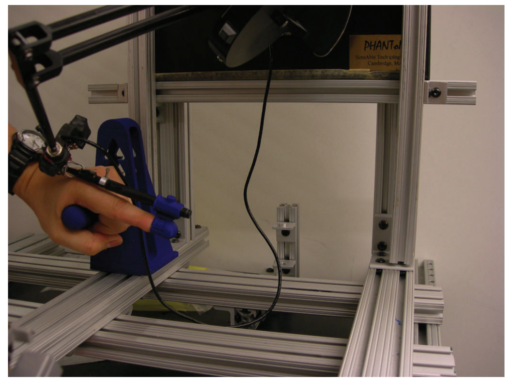

Fig. 1. Hardware interface of the Virtual Therapist

I. Introduction

Hand injuries are among the most frequent injuries that occur to the body, accounting for 7% to 29% of body injuries [1]. After finger or hand injury and subsequent surgery, patients are often instructed to start a rehabilitation plan immediately while pain and swelling are still diminishing. Rehabilitation may aim to avoid the occurrence of scar adhesions around wounded tendons, stiffness of joint capsules, shortening of muscles, and contracture of ligaments, which are important causes of reduced range of motion (ROM) [2]. Rehabilitation programs usually focus on regaining ROM and strengthening of the fingers, and they are conventionally guided by occupational therapists.

In recent years, researchers have designed and prototyped different mechatronic devices for rehabilitation. Some past research has suggested that an interface that could imitate the therapist's exercises would be beneficial, and such therapy could be functionally as good as or even better than conventional therapy [3]. In finger rehabilitation, most existing devices have been designed for hand impairment patients who have suffered from strokes and need intensive and repetitive therapy to increase sensorimotor cortex activation. For instance, work by [4]–[10] has employed exoskeleton structures to facilitate the hand's grasping and releasing movement; in [11], a magneto-rheological fluid-based glove was designed to achieve controllable resistance needed during the finger therapy; and in [12], a back-drivable linkage mechanism was integrated with virtual rehabilitation. However, due to their inherently complex design, both the exoskeleton and glove-based devices have to cover a large portion of the finger/hand surfaces in order to be stabilized during the finger's movement. The contact and rubbing can potentially cause excessive pain and even infection around the wounded areas, and therefore these devices are not suitable for applications in which patients need to initiate finger rehabilitation following hand surgery. Besides, the weight of the exoskeleton borne by the patient is often significant, resulting in a mandatory motion of the wrist/arm in order to maintain the exoskeleton's relationship with the finger [4]

Appropriately-designed robotic rehabilitation systems have the potential to provide additional benefits to the patient and therapist. The outcome of rehabilitation is affected not only by the therapy program and the rehabilitation devices but also by the motivation of the patient [13]. In addition to on-site rehabilitation advised by experienced hand therapists once or twice per week at a clinic, a finger rehabilitation program often requires four to five days of independent home exercises after surgery. With little or no guidance and supervision, patients exercising their fingers at home may find themselves less motivated to follow the required number of repetitions and may fail to reach the correct ROM during exercise [13]. On the other hand, from a doctor's point of view, being able to adjust a patient's therapy plan to his or her therapy progress in a timely and appropriate way is also crucial to the optimal recovery of the patient's hand function.

In this paper, we propose a haptic system, Virtual Therapist

Zhe Xu and Yoky Matsuoka are with the Department of Computer Science & Engineering, University of Washington, WA, USA, e-mail: zhexu@cs.washington.edu, yoky@cs.washington.edu

Rebecca Fiebrink is with the Department of Computer Science, Princeton University, NJ, USA, e-mail: fiebrink@princeton.edu

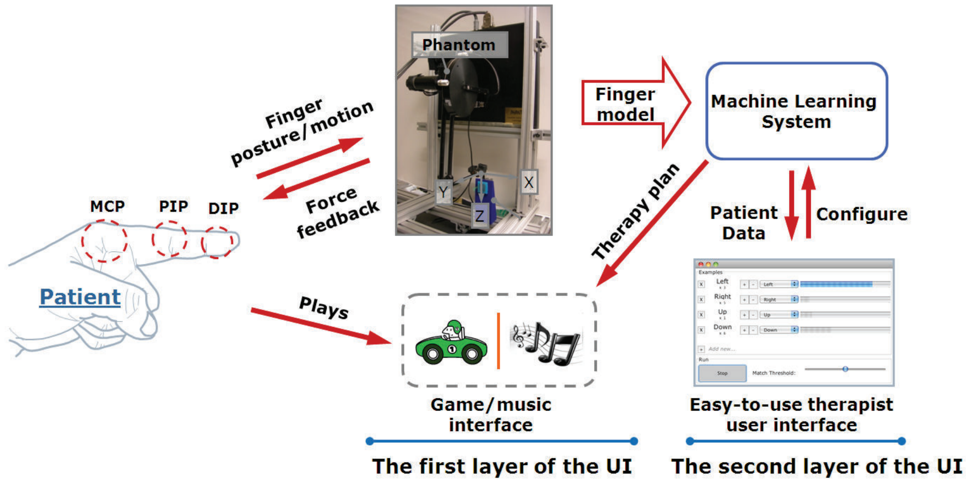

Fig. 2. Schematic drawing of important components of the Virtual Therapist.

(see Figure 1), that can provide an augmented interaction between a patient and a six degree-of-freedom Phantom robot. The design of the Virtual Therapist allows the full ROM of the finger while simultaneously providing model-based estimation of all joint angles. Both active and passive force feedback can be achieved by the Phantom robot with a maximum 8.5 N output force, which is sufficient for patients suffering from joint pain [14]. A fully-functional software interface has been developed and incorporated with the haptic system so that the therapist can easily assign and adjust patient-specific rehabilitation tasks by directly interacting with the patient's finger as they would usually do during a regular rehabilitation session. The following sections of the paper discuss the motivation for the design, provide a detailed overview of the haptic system, and describe how the system can be used by therapists and patients in a personalized treatment plan.

II. Design Motivation of Personalized Haptic System

Although post-stroke finger and hand rehabilitation is a more widely investigated domain, post-surgery rehabilitation poses a different set of challenges that must be considered in the design of mechatronic and robotic therapy devices. According to an interview with an experienced hand surgeon and therapist from the Harborview Medical Center in Seattle, Washington, early-stage finger therapy is crucial to a patient's full recovery, and patients need to start therapy shortly after surgery (often the following day). Otherwise, the scar adhesions around wounded areas can later cause reduced ROM of the finger and even require further surgery to remove them. In contrast to a post-stroke patient whose finger's skin, tendons and muscles often remain intact when the rehabilitation first commences, post-surgery patients often find that pain and swelling can make it challenging to accomplish the required repetitions of finger movements or advised ROM during the early stages of recovery. Although exoskeleton- or glove-based mechatronic and robotic devices have been successfully designed for post-stroke patient rehabilitation, post-surgery patients require less physical contact and milder external force than is typical of those devices.

We have therefore constructed a post-surgery rehabilitation system employing a commercial 6-DOF Phantom Premium 1.5A (SensAble Technologies, Inc., Wilmington, MA). This hardware is back-drivable and accurate (0.03 mm resolution with 0.04 N backdrive friction), is capable of providing controllable force of a magnitude sufficient for post-surgery rehabilitation exercises, and allows easy construction of a proof-of-concept system. As shown in Figure 1, after being carefully re-oriented and coupled only with the fingertip, the Phantom robot can provide enough workspace (195×270×375 mm) for full ROM of fingers of varying sizes while requiring minimal physical contact with the finger.

The design of an effective rehabilitation system must consider the needs and roles of both the patient and the professional therapist. Prior research has suggested a range of benefits of applying virtual reality to robot-aided hand rehabilitation [12], [15]. In particular, virtual rehabilitation can increase patient motivation for a longer period of time, thereby enhancing the effectiveness of therapy. At the same time, the guidance from a hand therapist plays an irreplaceable role during the early stage of post-surgery finger rehabilitation, and a robotic therapy tool should leverage the professional therapist's training, clinical experience, and ability to tailor a treatment plan to an individual patient. Unfortunately, a lack of computer skills on the part of therapists can present barriers to the effective employment of rehabilitation technologies [16], and such barriers may be magnified in technology that requires specialized application to different patients with different recovery plans.

In order to improve patient motivation while also reducing barriers to therapist customization of the rehabilitation system, we designed a two-layer software interface for the Virtual Therapist. Motivated by goal-setting theory [17], the patient-facing first layer of the UI provides patients with the ability to interact with entertaining and encouraging stimuli—music and online games—during their finger therapy regime. The second, therapist-facing layer of the UI provides the therapist with a graphical interface to demonstrate any number of recommended finger movements while advising patients in-clinic. Once the therapist has demonstrated one or more patient-specific finger movements to the system, the patient can use these motions to control games or music.

III. System Overview

This section describes in detail the implementation and functionality of each component of the Virtual Therapist: the model of the human finger that allows us to precisely measure joint position when the fingertip is coupled to the Phantom, the mechanical design for coupling the finger to the Phantom, and the software mechanisms that allow therapists to design patient-specific exercises and that allow patients to use these exercises in playing games and music.

A. Human Finger Modeling

Detailed measurements of the ROM and DOFs of an injured finger can be used in the design of precise and flexible virtual therapy systems (e.g., to provide positive feedback when a target ROM is achieved), as well as to provide data for the therapist and patient to track progress over time. However, existing finger or hand rehabilitation technologies are not capable of measuring or estimating the full ROM and DOFs of the finger without using complicated exoskeleton mechanisms [12]. In our previous work, we have developed the Anatomically Correct Testbed (ACT) Hand as a platform for better understanding the biomechanics of the human hand and developing artificial neural control strategies for dexterous manipulation [18]–[20]. The ACT Hand is a working, robotic hand system whose biomechanical properties are designed to most closely replicate their human counterparts (e.g. length of the phalanges, true-to-life bone shapes, and correct ROM and DOFs), so it was used as a substitute of the human hand during the early stage of developing and testing the finger model for the Virtual Therapist (see Figure 4).

As shown in Figure 3, there are three joints in the index finger: namely, the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP). The PIP joint is located at the distal end of the proximal phalangeal bone, and the DIP joint is located at the distal end of the middle phalangeal bone. The MCP joint has two DOFs: one to achieve flexion-extension and another to realize abduction-adduction finger motion. According to the anatomical joint properties of the human index finger, the abduction-adduction joint axis is oriented at 60° with respect to the metacarpophalangeal bone as shown in Figure 3.

After choosing the correct finger model, kinematic analysis of the index finger is conducted based on Denavit-Hartenberg (DH) notation, and corresponding parameters are summarized in Table I.

A key benefit of the using model-based joint angle estimation is that we can extract all the joint information from

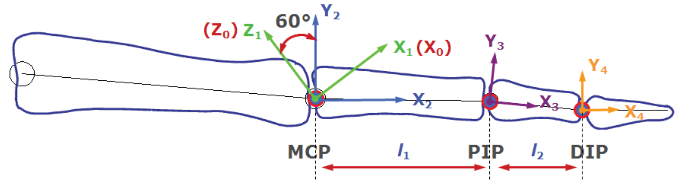

Fig. 3. Model of the human index finger.
Frame 0: Fixed frame (palm phalange)
Frame 1: Adduction/Abduction frame
Frame 2: MCP flexion frame
Frame 3: PIP flexion frame
Frame 4: DIP flexion frame

TABLE I
Denavit-Hartenberg parameters used in the index finger model

Linkage No. i	α_{i-1}	a_{i-1}	d_{i-1}	θ_i
1	0°	0	0	ω (MCP ab-ad)
2	90°	0	0	$\theta_1-30°$ (MCP flexion)
3	0°	l_1	0	θ_2 (PIP flexion)
4	0°	l_2	0	θ_3 (DIP flexion)

The z-axis is in the direction of the joint axis.
α_{i-1}: Angle about common normal, from old z-axis to new z-axis.
a_{i-1}: Length of the common normal. Assuming a revolute joint, this is the radius about previous z.
d_{i-1}: Offset along previous z to the common normal.
θ: Angle about previous z, from old x to new x.

knowing only the information at the fingertip. In this way, a patient can face fewer physical constrains if splints and bandages are used after surgery. The information collected from the fingertip is used to recover the four joint angles (θ_1, θ_2, θ_3, ω) through a series of matrix transformations as follows:

$$ {}^0_4T = {}^0_1T \cdot {}^1_2T \cdot {}^2_3T \cdot {}^3_4T \tag{1} $$

The final format of the transformation matrix ${}^0_4T$ can be further sorted into the following format:

$$ {}^0_4T = \left\{ \begin{array}{cccc} f(\theta_{1,2,3},\omega) & f(\theta_{1,2,3},\omega) & \sin\omega & f(\theta_{1,2,3},\omega,l_{1,2}) \\ f(\theta_{1,2,3},\omega) & f(\theta_{1,2,3},\omega) & \cos\omega & f(\theta_{1,2,3},\omega,l_{1,2}) \\ f(\theta_{1,2,3}) & f(\theta_{1,2,3}) & 0 & f(\theta_{1,2,3},l_{1,2}) \\ 0 & 0 & 0 & 1 \end{array} \right\}. $$

B. Finger-Phantom Modeling

As listed in Eq. (1), our goal is to compute all four joint angles while the patient's fingertip is connected with the end effector of the Phantom robot. In order to solve the set of analytical equations composed by the entries of this 4x4 matrix, we need to provide numerical values for the right-hand-side of the equations. The Phantom robot is used to accurately measure these values through a series of coordinate transformations as shown in Figure 4.

The matrix representing the transformation from distal joint frame *D* to index frame *I* can be derived through the following equation:

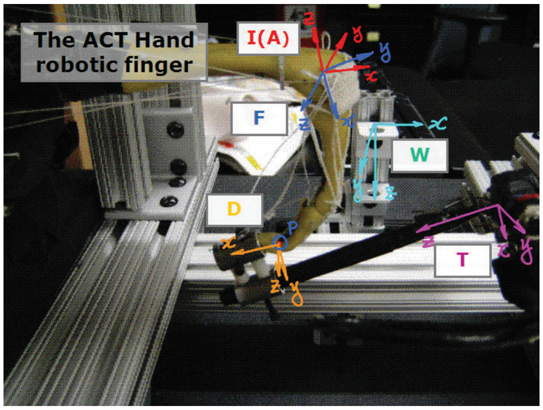

Fig. 4. Correlation of coordinate systems between the finger and Phantom robot.
Frame W: Workspace frame
Frame T: Touch frame
Frame I: Index frame
Frame A: Adduction/Abduction frame
Frame F: Flexion/Extension frame
Frame D: Distal joint frame

$$ {}^{I}_{D}T = {}^{I}_{W}T \cdot {}^{W}_{T}T \cdot {}^{T}_{D}T \tag{2} $$

On the right-hand-side of the above equation, the value of each matrix can be uniquely identified based on several callback functions provided by the Phantom robot's software framework. This makes ${}^{I}_{D}T$ a known variable. Thus, through the following correlation,

$$ {}^{I}_{D}T = {}^{0}_{4}T \tag{3} $$

we are able to solve the values for MCP flexion/extension (θ_1), PIP flexion/extension (θ_2), DIP flexion/extension (θ_3), and MCP adduction/abduction (ω). Note that the length of each link ($l_{1,2}$) is a constant provided by a hand surgeon prior to the surgery.

C. Mechanical Design for Coupling the Patient's Finger

Having described the algorithm for determining finger joint angles using the Phantom, we now describe the physical interaction between the patient and the Virtual Therapist hardware.

As shown in Figure 5, the handle jig is designed to accommodate patients with different physical conditions by incorporating an adjustable handle. The connector used to fix the fingertip with the end-effector of the Phantom is shown in the bottom right side of Figure 5, and it is 3D printed by the Dimension BST 768 (Stratasys Corp., Eden Prairie, MN) therefore can easily be customized to meet the needs of patients with differing fingertip sizes and shapes to realize non-slip coupling.

D. Personalized Therapy Environment

The Virtual Therapist system as described above offers two important advantages that make it especially suited to application in personalized post-surgery rehabilitation. First, the coupling between the fingertip and Phantom does not

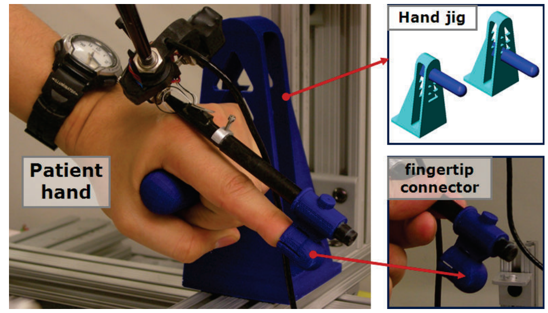

Fig. 5. Adjustable handle jig and fingertip connector.

place any constraints on possible finger positions or motions, so any therapy motions or exercises that can be performed "freehand" without coupling to the system (such as those used in conventional therapy regimes in the absence of robotics technology) can also be performed in conjunction with the Virtual Therapist. Second, the system estimates all joint angles, which means that it can be employed in therapy regimes in which a therapist wishes to focus on measuring and improving the ROM of each joint individually.

We have constructed a software framework that takes advantage of these two aspects of the system, in which therapists can configure a therapy regime consisting of one or more personalized finger exercises that the patient can execute to play a game or music. Two types of exercises are currently supported: *target acquisition* and *trajectory following*. In target acquisition, the goal for the patient is to move the finger into a target position, such as in Figure 6(a). The target position can be defined for all joints or for any subset of joints. The system identifies a patient's finger position as matching a target if the distance between the patient's joint angles and any demonstrated example of that target is within a specified threshold. In trajectory following, the goal for the patient is to move the finger through a predefined motion trajectory, such as in Figure 6(b). The system uses dynamic time warping (see, e.g., [21]) to continuously compute the distance between a patient's current motion trajectory and all recorded trajectory demonstrations, and it identifies a match if the distance to any demonstration falls within a specified threshold. The system is capable of recognizing simple gestures, such as linear motion in different directions, as well as more complex gestures such as shapes of different sizes and orientations or letters of the alphabet drawn in space. The dynamic time warping threshold allows patient gestures to be matched to the demonstrations in the presence of deviations in both space and time (e.g., speed and smoothness of execution).

1) Therapist Interface: Virtual Therapist allows the professional human therapist to assign arbitrary target positions and motion trajectories to a patient, as well as to fine-tune the matching thresholds used for targets and trajectories. The system is therefore significantly more flexible than prior rehabilitation systems, such as that of [22], in which the therapy motions are limited and pre-defined in hardware and software. This added flexibility has required the implementation an easy-

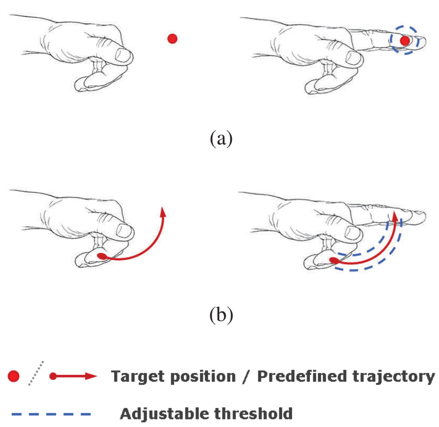

Fig. 6. Two types of implemented rehabilitation exercises. (a) Example of the target acquisition exercise. (b) Example of the trajectory following exercise.

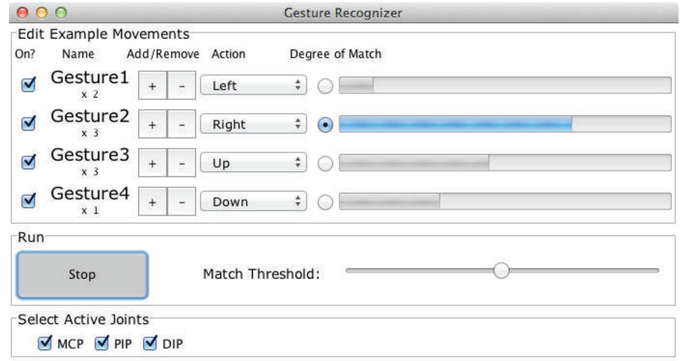

Fig. 7. The therapist user interface. Each row in the GUI corresponds to one exercise target position or motion trajectory. From left to right, each row allows the exercise to be enabled or disabled, displays the name of the exercise and the number of examples that have been demonstrated, allows examples to be added or deleted, allows the choice of the keypress that will be triggered by each exercise (in GamePlayer mode), and displays the current degree of match to each exercise. If the degree of match meets the specified threshold for an exercise, its matching bar lights up and the corresponding action (e.g., keypress) is triggered.

to-use therapist user interface for system customization, which does not rely on the therapist possessing significant technical expertise. Our software therefore employs a lightweight demonstration-based paradigm whereby a therapist simply demonstrates one or more examples of each exercise that a patient should execute.

Figure 7 shows the graphical user interface for interactive therapy motion demonstration. The therapist can specify an arbitrary number of therapy targets or trajectories, then add example demonstrations of each one by guiding the patient's finger to the target position or through the target motion. Once one or more examples have been added, the patient can attempt to execute the prescribed target position or trajectory, and the user interface will dynamically display the closeness of match detected between the patient's action and the demonstrated example(s). The therapist can use the slider to adjust the matching threshold in order to ensure that only patient actions that are judged to be acceptably accurate executions of the prescribed exercises are recognized as such by the system. Whenever the system recognizes that a target position or trajectory has been correctly executed according to the current threshold, it provides visual feedback by lighting up the corresponding exercise in the GUI.

In the case of therapy robots that accommodate only a fixed vocabulary of therapy exercises that is known in advance by the therapy software developers, the developers are able to preprogram each therapy exercise to trigger an appropriate system response. For example, [22] matched a hand grasp motion to vertical navigation and a pronation/supination motion to horizontal navigation in a virtual maze. In the Virtual Therapist system, however, therapists are free to define any number or type of therapy gestures, and it is not known in advance which gaming controls (or even which games) will be well-matched to the speed, difficulty, and other qualities of the prescribed exercises. Virtual Therapist therefore allows therapy motions to be used to play either music or arbitrary online games in a manner that is customizable by the therapist and patient.

2) Music and Game Applications: We have implemented two music applications for use in therapy programs in which the patient must execute many repetitions of one or more motions. In MelodyPlayer, each successful exercise execution (i.e., acquisition of a single target or execution of a single trajectory) triggers the playing of the next note in a melodic sequence. This application encourages the patient to execute a sequence of exercises with more or less precise timing, so that he may hear the melody played back properly. In AudioPlayer, the patient is also asked to execute a sequence of the prescribed exercises, and to do so at a tempo corresponding to a song. AudioPlayer is motivated by prior research demonstrating benefits of rhythmic timekeeping in physical therapy (e.g., [23]), and the song may be chosen to reflect the patient's taste and the therapist's target tempo. AudioPlayer encourages the patient to execute the exercises at the given tempo by slowing down the audio playback in a comedic manner until the correct exercise tempo is resumed.

Finally, the GamePlayer mode of Virtual Therapist allows the patient or therapist to assign each finger target position or trajectory to a single control of an arbitrary keyboard-controlled game. In GamePlayer, each successful execution of a therapy exercise results in a simulated keypress, where the key to be pressed is selected using the user interface show in Figure 7. Many keyboard-controlled games can be found for free on the Internet[1], and users can choose games where the gameplay (e.g., number and type of controls, speed and difficulty) is well-matched to the therapy exercises. For example, a two-target acquisition task may be well-matched to playing 2D paddle games (e.g., Pong), and a four-target task might be well-matched to playing simple maze games.

3) Validation: We recruited three human adults with uninjured fingers to provide a preliminary validation of the efficacy

[1] e.g., http://www.flashrolls.com/fun-games/Ultimate-Ping-Pong-Flash-Game.htm

of our proposed system. Each participant was alternately assigned the role of patient and therapist, and "patients" employed the GamePlayer mode to play an online maze game[2]. Four groups of arbitrary finger postures were chosen by the "therapists" for the "patients" to trigger the four direction controls of the animated character in the maze. All of the "patients" were able to immediately start playing the game, and they all successfully passed two stages of the maze within three minutes. It took all "therapists" fewer than eight minutes of instruction and practice to learn how to correctly use the therapist GUI. All the "patients" and "therapists" verbally indicated that they were satisfied with the system.

IV. Conclusion and future work

We have described a haptic system for personalized post-surgery finger rehabilitation. Our proof-of-concept system makes use of the following main components: a 6-DOF commercial Phantom robot used to physically interact with the patient, an anatomically correct index finger model derived for extracting joint angles from the patient's fingertip position, and a software environment that provides therapists an easy way to define patient-specific rehabilitation exercises through real-time demonstration and that allows patients to employ these exercises to control games or music. This work offers significant benefits compared to past work in that it requires minimal contact between the rehabilitation mechatronics and injured finger, allows and is capable of recognizing arbitrary finger motions, can precisely compute individual joint angles for use in treatment monitoring or therapy activities, and offers a demonstration-based mechanism for therapists to define a customized therapy plan without needing significant technical expertise.

Our next step is to initiate a study with finger therapy patients for quantitatively investigating how our system may improve the outcome of their post-surgery finger rehabilitation. We would like to incorporate different rehabilitation robotic systems, including an exoskeleton mechanism, with our two-layer software interface. We believe our working system will provide greater insight into future designs of personalized rehabilitation systems for better serving patients and therapists.

V. Acknowledgements

The authors thank Dr. Christopher Allan and Mr. Thomas McClure at the HarborView Medical Center for their tremendous help on providing insights into the formation of this project.

References

[1] M. Trybus, J. Lorkowski, L. Brongel, and W. Hladki, "Causes and consequences of hand injuries," *The American Journal of Surgery*, vol. 192, no. 1, pp. 52 – 57, 2006.

[2] U. Guzelkucuk, I. Duman, M. A. Taskaynatan, and K. Dincer, "Comparison of therapeutic activities with therapeutic exercises in the rehabilitation of young adult patients with hand injuries," *The Journal of Hand Surgery*, vol. 32, no. 9, pp. 1429 – 1435, 2007.

[3] V. Huang and J. Krakauer, "Robotic neurorehabilitation: A computational motor learning perspective," *Journal of NeuroEngineering and Rehabilitation*, vol. 6, no. 1, p. 5, 2009.

[4] T. Worsnopp, M. Peshkin, J. Colgate, and D. Kamper, "An actuated finger exoskeleton for hand rehabilitation following stroke," in *IEEE 10th International Conference on Rehabilitation Robotics*, June 2007, pp. 896–901.

[5] A. Chiri, N. Vitiello, F. Giovacchini, S. Roccella, F. Vecchi, and M. C. Carrozza, "Mechatronic design and characterization of the index finger module of a hand exoskeleton for post-stroke rehabilitation," *IEEE/ASME Transactions on Mechatronics*, no. 99, pp. 1–11, 2011.

[6] Y. Fu, P. Wang, S. Wang, H. Liu, and F. Zhang, "Design and development of a portable exoskeleton based cpm machine for rehabilitation of hand injuries," in *IEEE International Conference on Robotics and Biomimetics*, Dec. 2007, pp. 1476–1481.

[7] A. Chiri, F. Giovacchini, N. Vitiello, E. Cattin, S. Roccella, F. Vecchi, and M. Carrozza, "HANDEXOS: Towards an exoskeleton device for the rehabilitation of the hand," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct. 2009, pp. 1106–1111.

[8] J. Wang, J. Li, Y. Zhang, and S. Wang, "Design of an exoskeleton for index finger rehabilitation," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Sep. 2009, pp. 5957–5960.

[9] J. Li, R. Zheng, Y. Zhang, and J. Yao, "iHandRehab: An interactive hand exoskeleton for active and passive rehabilitation," in *IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2011, pp. 1–6.

[10] A. Wege, K. Kondak, and G. Hommel, "Mechanical design and motion control of a hand exoskeleton for rehabilitation," in *2005 IEEE International Conference on Mechatronics and Automation*, vol. 1, 2005, pp. 155–159.

[11] S. Winter and M. Bouzit, "Use of magnetorheological fluid in a force feedback glove," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 1, pp. 2–8, March 2007.

[12] U. Mali and M. Munih, "Haptic interface for finger exercise and virtual rehabilitation," in *The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, Feb. 2006, pp. 243–248.

[13] J. Case-Smith, "Outcomes in hand rehabilitation using occupational therapy services," *The American Journal of Occupational Therapy*, vol. 57, no. 5, pp. 499–506, 2003.

[14] S. Olandersson, H. Lundqvist, M. Bengtsson, M. Lundahl, A.-J. Baerveldt, and M. Hilliges, "Finger-force measurement-device for hand rehabilitation," pp. 135 – 138, 2005.

[15] V. Popescu, G. Burdea, M. Bouzit, and V. Hentz, "A virtual-reality-based telerehabilitation system with force feedback," *IEEE Transactions on Information Technology in Biomedicine*, vol. 4, no. 1, pp. 45–51, march 2000.

[16] G. Burdea, "Virtual rehabilitation: Benefits and challenges," *Methods Inf. Med.*, vol. 42, no. 5, pp. 519–23, 2003.

[17] E. A. Locke and G. P. Latham, "Building a practically useful theory of goal setting and task motivation: A 35-year odyssey," *American Psychologist*, vol. 57, no. 9, pp. 705–717, 2002.

[18] D. Wilkinson, M. Vande Weghe, and Y. Matsuoka, "An extensor mechanism for an anatomical robotic hand," in *Proceedings of the 2003 IEEE International Conference on Robotics and Automation*, 2003.

[19] M. Vande Weghe, M. Rogers, M. Weissert, and Y. Matsuoka, "The ACT hand: Design of the skeletal structure," in *Proceedings of the 2004 IEEE International Conference on Robotics and Automation*, 2004.

[20] L. Y. Chang and Y. Matsuoka, "A kinematic thumb model for the ACT hand," in *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*, 2006.

[21] S. Salvador and P. Chan, "Toward accurate dynamic time warping in linear time and space," *Intelligent Data Analysis*, vol. 11, pp. 561–580, October 2007.

[22] O. Unluhisarcikli, B. Weinberg, M. Sivak, A. Mirelman, P. Bonato, and C. Mavroidis, "A robotic hand rehabilitation system with interactive gaming using novel electro-rheological fluid based actuators," in *Proceedings of IEEE International Conference on Robotics and Automation*, 2010, pp. 1846–1851.

[23] M. Thaut, G. McIntosh, and R. Rice, "Rhythmic facilitation of gait training in hemiparetic stroke rehabilitation," *Journal of the Neurological Sciences*, vol. 151, no. 2, pp. 207 – 212, 1997.

[2] http://mazegame.net/robotmaze.html