Hand Rehabilitation Learning System With an Exoskeleton Robotic Glove

Zhou Ma, *Student Member, IEEE*, Pinhas Ben-Tzvi, *Senior Member, IEEE*, and Jerome Danoff

***Abstract*—This paper presents a hand rehabilitation learning system, the SAFE Glove, a device that can be utilized to enhance the rehabilitation of subjects with disabilities. This system is able to learn fingertip motion and force for grasping different objects and then record and analyze the common movements of hand function including grip and release patterns. The glove is then able to reproduce these movement patterns in playback fashion to assist a weakened hand to accomplish these movements, or to modulate the assistive level based on the user's or therapist's intent for the purpose of hand rehabilitation therapy. Preliminary data have been collected from healthy hands. To demonstrate the glove's ability to manipulate the hand, the glove has been fitted on a wooden hand and the grasping of various objects was performed. To further prove that hands can be safely driven by this haptic mechanism, force sensor readings placed between each finger and the mechanism are plotted. These experimental results demonstrate the potential of the proposed system in rehabilitation therapy.**

***Index Terms*—Exoskeleton, force feedback, grasping, rehabilitation.**

I. Introduction

OVER the past decade, significant work has been done and published in the field of haptic gloves, particularly in the application of rehabilitation [1], [2]. However, compared to well-developed force feedback rehabilitation devices for larger body areas such as upper [3], [4] and lower limbs [5], [6], hand haptic gloves still face many challenges due to the hand's smaller size and rich sensing and complex motion capabilities [7].

Force-displaying haptic gloves for rehabilitation are still in an early stage of development as none of them has been commonly used in clinical applications [1]. Haptic gloves could fit roughly two categories: 1) body-based/portable haptic gloves [8]–[15]; and 2) ground-based haptic gloves [16]–[21].

Body-based gloves fit over the user's hand and have the advantage of a wider motion range compared to the ground-based devices. Another benefit is that they can measure and actuate the fingers' motion more easily as they are kinematically similar to human hands. But excessive device weight becomes an issue for these units due to the user's fatigue, which can lead to hand and arm pain.

The RMII-ND Glove [10] is the most cited noncommercial haptic glove that can be used for hand function diagnosis and rehabilitation. The system includes a PC workstation, Smart Controller Interface and Rutgers MasterII-ND force feedback glove. By actuating a pneumatic piston located inside the palm, the glove can generate a force of up to 16 N to each finger (excluding the little finger), in the direction of closing of the hand (single direction force). Unlike the other devices, the RMII-ND develops fingertip forces from inside the palm rather than the dorsum. With a weight of only 100 grams, the glove is lightweight and comfortable to wear. Each piston has sensors to measure its displacement and the finger position. An air compressor and other supporting devices are required to power and control the RMII-ND.

WorldToolKit (Virtual Reality tool box) [22] was used to develop a 3D interface shown on a desktop display. The user can interact with virtual objects in 3D GUI with different hand gestures such as grasp, lateral pinch, pointing and release. Different exercise routines were created for hand rehabilitation exercises: a rubber ball for squeezing exercises, "silly putty" for gripping or pinching exercises, Digi-Key for individual finger exercise, and the functional tasks of peg board insertion and ball throwing. Tele-rehabilitation capability has also been developed and tested for the system. However, the RMII-ND glove may be limited in its applications to laboratory and clinical settings. This is due to its limited workspace, the heavy weight of the air compressor and potential difficulty for patients who are affected with spasticity and their ability to put on the glove.

The RoboGlove [13] is a robotic device created to augment the hand strength of the user for rehabilitation application. RoboGlove is comprised of two sections: the forearm module and the glove module. Three actuators, control electronics, and a fabric cover are contained within the forearm module. The glove modules include a glove, a conduit anchor and five FSR sensors at the finger tips. The conduit anchor is used to prevent the tendon from exerting a force/moment on the user's wrist. By routing tendons to all five fingers, the device can exert a continuous grasp force up to 66 N. As RoboGlove is designed to assist hand motion in the direction of flexion, there is only one tendon for each finger to provide augmentation of the grasping force. The device weights about 770 grams and is available in three different sizes to accommodate different hand sizes.

Manuscript received April 13, 2015; revised August 29, 2015; accepted October 17, 2015. Date of publication November 19, 2015; date of current version December 06, 2016.

Z. Ma is with US Med Innovations, Takoma Park, MD 20912 USA.

P. Ben-Tzvi is with the Robotics and Mechatronics Lab, Virginia Tech, Blacksburg, VA 24061 USA (e-mail: bentzvi@vt.edu).

J. Danoff is with the Department of Exercise and Nutrition Sciences, School of Public Health, George Washington University, Washington, DC 20052 USA.

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Digital Object Identifier 10.1109/TNSRE.2015.2501748

Unlike portable haptic gloves, ground-based devices are fixed and designed to be used while the user is sitting. Thus, the user's freedom of motion is limited when compared to portable haptic gloves.

The Gifu Hand Motion Assist Robot [18] was designed to assist finger exercise motions for hemiplegic patients. The device is intended to reproduce the movements of a healthy hand. The CyberGlove was used to measure individual finger joint motions of the healthy hand and control the exoskeleton device (the Gifu Hand) to support the motion of the impaired hand. This procedure is considered self-controlled rehabilitation therapy. The device was constructed with 18 DOFs: 3 DOF for each finger, 4 DOF for the thumb and 2 DOF for the wrist to assist finger and thumb independent motions such as flexion/extension and abduction/adduction, thumb opposability and hand-wrist coordinated motions.

One purpose of rehabilitation is for subjects with a variety of sensory, motor or neurological impairments to relearn basic motor tasks. The exact type of impairment may vary for different patients. The haptic glove for hand rehabilitation needs to be flexible to accommodate these differences so that the training can be easily adjusted to the needs of each subject. Flexibility of the haptic glove design helps ensure that the hand training tasks resemble healthy subjects' finger movements as much as possible. Safety is another fundamental rule that must be considered in rehabilitation training. Also, the extra weight imposed on the hand will be even more difficult to handle for the patients, because the heavy glove can easily exhaust the user.

Previously, we have presented the design of a robotic haptic exoskeleton device (SAFE Glove) to measure the user's hand motion and assist hand motion while remaining portable and lightweight [23], [24]. The device consists of a five-finger mechanism actuated with miniature DC motors through antagonistically routed cables at each finger, which act as both active and passive force actuators. The glove system is a wireless and self-contained mechatronic system that mounts over the dorsum of a bare hand and provides haptic force feedback to each finger. The glove is adaptable to a wide variety of finger sizes without constraining the range of motion. This makes it possible to accurately and comfortably track the complex motion of the finger and thumb joints associated with common movements of hand functions, including grip and release patterns.

In this paper, we propose a hand rehabilitation learning system utilizing the latest model of the SAFE Glove [23] to develop a model of fingertip motion and force data so that the glove can assist any user to grasp different objects. The paper is organized as follows. Section II introduces the overview of the rehabilitation learning system. Section III discusses how each module of the system is implemented with the glove system. Section IV describes several experiments to evaluate the proposed hand rehabilitation system. Finally, Section V provides the conclusions and future work.

II. Framework of the Rehabilitation Learning System

A. Overview of the Rehabilitation Learning System

A full grasping learning and rehabilitation system has been developed that is capable of measuring and learning from

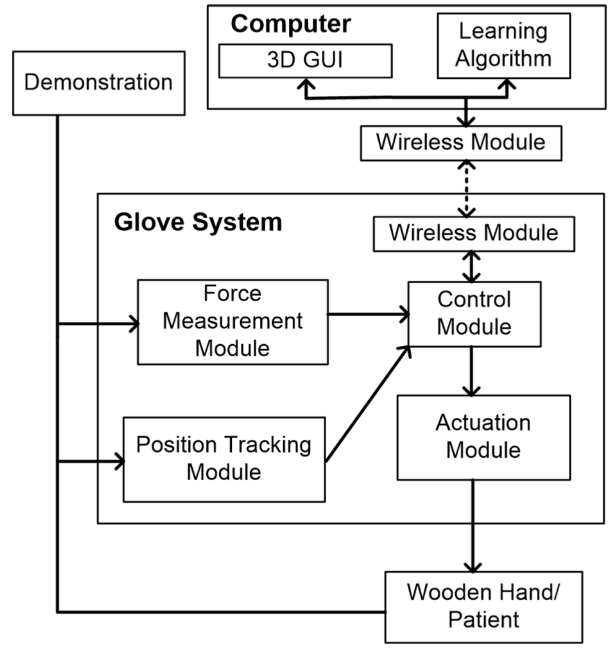

Fig. 1. Rehabilitation learning system overview.

human grasping motions and providing rehabilitation function to the user. The system overview is shown in Fig. 1. There are four components: the demonstration procedure, the SAFE Glove system, the machine learning algorithm and a 3D GUI program, and the rehabilitation/assistive engineering procedure. Among them, the SAFE Glove and the learning algorithm are the center pieces of the whole system. The SAFE Glove measures both motion and force information in the grasping procedure demonstration. The authors propose that the trajectories of grasping gesture and contact force for different people follow the Gaussian distribution. Thus the captured motion and force data are used to train a Gaussian Mixture Model (GMM) [25], which also represents the distribution of the joint data. The learned motion and force information representing skill is then mapped to the SAFE Glove to actuate/assist a wooden hand/user to generate proper motions and force to accomplish the learned tasks. Through the 3D GUI interface, the user can watch and manipulate the virtual hand and objects in a Head Mounted Device (HMD) in 3D in real-time.

The procedure of reproducing grasp from demonstration data is divided into four stages. In the first stage, the demonstration procedure is carried out to record common movements of hand function including grip and release patterns. In the second stage, the motion and force sequences of different trials are processed and aligned together by a dynamic time warping (DTW) method [26]. In the third stage, the processed demonstration sequences are encoded by a GMM, a machine learning approach. To have the learning results applied on the glove, in the final stage, a motion and force sequence is generated from the GMM by Gaussian Mixture Regression (GMR).

B. Glove System

The multi-link finger mechanism provides flexion/extension and abduction/adduction at the proximal joint, and the glove mechanism configuration (Fig. 2) allows the glove mechanism

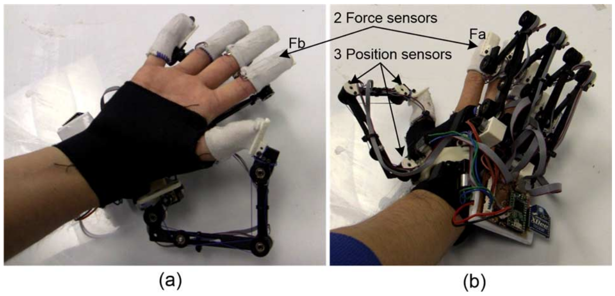

Fig. 2. SAFE Glove prototype worn on a hand.

to adapt to different finger sizes. The glove uses a miniature DC motor with high reduction ratio and an antagonistically routed cable mechanism at each finger as both active and passive force actuators. As shown in Fig. 2, on each finger, there are three position sensors and two force sensors. The position sensors provide accurate joint angles to calculate the finger tip position. The force sensor Fa (Fig. 2) is located on the finger nail to measure the contact force between the glove mechanism and the finger. The force sensor Fb is under the finger pad to measure the force between the finger and the grasping object.

The primary advantages of the SAFE Glove are as follows. First, it is light-weight (430 g), which reduces user fatigue, and the wireless communication capability with a PC or a mobile robot greatly increases its portability. Second, the mechanical design is compact without limiting the natural range of motion of human fingers. Third, it can accurately measure the hand kinematics and provide force feedback information. Fourth, the SAFE Glove is inexpensive. Finally, the system is safe for the user and can run for over one hour of continuous operation before the need to recharge.

C. Motion and Force Learning System

The purpose of the learning procedure is to actuate/assist the patient's hand to reproduce a similar grasp to the recorded demonstration. Since the data are different across demonstration trials (slightly different initial positions, speed, joint angles, etc.), the grasp is to be modeled from the demonstration data to generalize across multiple stored trials. In this section, a statistical modeling approach is used to train a learning model with the human demonstration data, so that the SAFE Glove can learn the high dimensional motion and force pattern from a human.

The motion and force data can be treated as a high dimensional time series. The sequences of multiple subjects performing similar activities vary slightly with respect to the magnitude and velocity. DTW is well known as a temporal alignment technique to find an optimal alignment of a multiple time series. Intuitively, the sequences are warped nonlinearly to match each other. DTW has been widely used in the field of machine learning, such as in speech recognition, activity recognition, synthesis of human motion for animation, etc. Here, we apply a typical DTW method that uses an optimization approach to find the optimal alignment of the data sequence to a reference sequence that minimizes the sum-of-square of the vertical distance between the reference sequence and the aligned sequence. Fig. 3 shows an example of the DTW result after the aligned motion data.

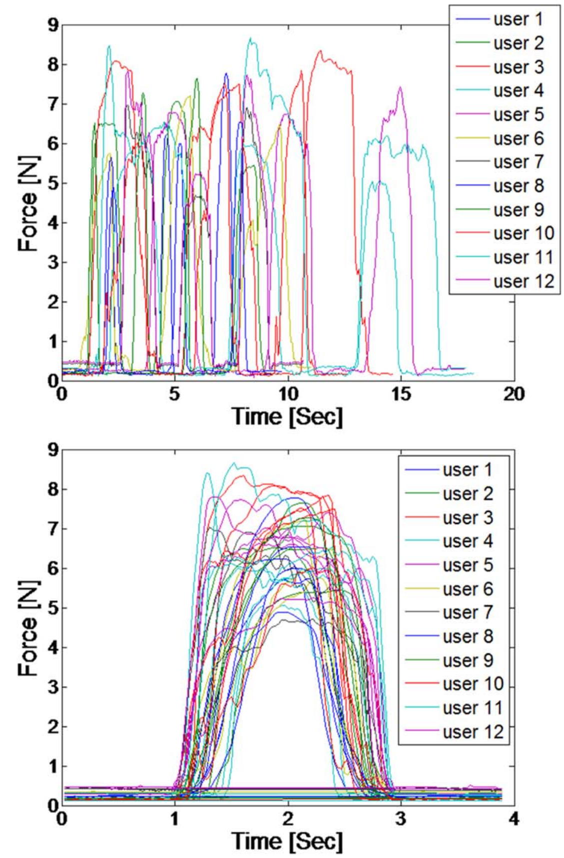

Fig. 3. DTW result for index force data. (top): raw data; (bottom): DTW result.

This statistical modeling is a promising approach to encode human behavior while taking into consideration the variance existing among multiple trials and subjects (for the same behavior). Given a data set $\xi_j = \{\xi_{j,t}, \xi_{j,m}, \xi_{j,f}\}_{j=1}^{N}$ of human demonstration, where N is the number of observations; $\xi_{j,t}$ is the time stamp, $\xi_{j,m} \in \Re^D$ is the D-vector of motion sequence, D is the number of joints; $\xi_{j,m} \in \Re^3$ is the force vector. The data set can be represented by a probabilistic model, the Gausian Mixture Model (GMM), which is a mixture of K Gaussian distributions, given by

$$p(\xi_j) = \sum_{k=1}^{K} p(k) p(\xi_j \mid k) \tag{1}$$

where $p(k)$ is the mixture weight, or the prior probability of the k^{th} distribution, $\sum_{k=1}^{K} p(k)$; $p(\xi_j \mid k)$ is the conditional probability of the observation ξ_j given the mixture component k. $p(\xi \mid k)$ is a Gaussian distribution characterized with means μ_k, and covariance Σ_k

$$p(k) = \pi_k \tag{2}$$

$$\begin{aligned} p(\xi_j \mid k) &= N(\xi_j; \mu_k, \Sigma_k) \\ &= \frac{1}{\sqrt{(2\pi)^D |\Sigma_k|}} e^{-\frac{1}{2}\left((\xi_j - \mu_k)^T {\Sigma_k}^{-1} (\xi_j - \mu_k)\right)}. \end{aligned} \tag{3}$$

The parameters π_k, μ_k, Σ_k are updated using the Expectation Maximization (EM) algorithm to best fit the observation with the probability model.

We define the mixture component $K = 3$, because the grasping process was segmented into three states: grasp the object, lift and place back the object, and release the object.

D. Mapping Learning Result to a Passive (Wooden) Hand System

Given a joint probability distribution $p(\xi_t, \xi_m)$ and $p(\xi_t, \xi_f)$ of the dataset modeled by a GMM, GMR computes a generalized trajectory by estimating $E[p(\xi_m \mid \xi_t)]$ and $E[p(\xi_f \mid \xi_t)]$, thus retrieving a motion point and force point at each time step ξ_t.

Then the glove follows these motion and force trajectories, generating grasping patterns in playback fashion and actuating or assisting a wooden (or subject's) hand to accomplish these movements. The glove adapts a hybrid motion and force controller to ensure the finger of the user's hand keeps contact with the object with a certain force, which was generated from the GMR. The force trajectory is used as the main input for the haptic controller. For the power grasping tasks, which are the type of grasping tasks we chose, we believe that the grasping force is more important than the finger closing angles. During grasping, the position data is mainly used to protect the user fingers from reaching to the limit positions. In this research, only the normal force is controlled due to the limitation of the force sensing resistors (FSR) sensor used.

E. 3D GUI for Training Rehabilitation

The GUI not only provides force and motion information of the hand for the user and hand therapist to view, but also works as a virtual-reality environment to interact with the glove system for the purpose of hand rehabilitation exercising.

Haptic gloves are used to both mediate the user's input into the 3D GUI simulation and to provide feedback from the simulation in response to this input. Thus, haptic gloves have both sensory and display channels.

During virtual-reality hand exercising, the haptic glove contact surfaces convey important sensory information that helps users grasp and manipulate virtual objects in the environment. When added to 3D visual feedback, haptic feedback greatly improves simulation realism [27], [28].

III. System Implementation

A. Finger Position Tracking Module

The glove consists of a sensorized exoskeleton worn on the dorsum (back) of the user's hand. The three joint positions of each finger of the user are measured by three miniature plastic precision potentiometers with a precision of 0.09° (12 bit AD converter). Wires from each sensor are routed through the finger links and then connected to the main controller. Since the sensors produce an analog signal, the length of the connection cables and the connections are optimized to minimize the resistive losses. An AD multiplexer and a 12-bit AD converter are used on the main controller to sample the tracking information at more than 1000 Hz.

The dimensions of each link segment are known a priori and used by the direct kinematics computational model stored in the controller. This model allows the determination of the position and orientation of each fingertip relative to the palm, based on the real-time position readings of the position sensors.

Using position sensors and links to track the finger positions has certain advantages when compared with other tracking systems. Our method is simpler and easier to use. Its accuracy is fairly constant over the whole finger workspace, and depends essentially on the resolution of the AD converter used. Unlike electromagnetic tracking systems, our method is immune to interference from metallic structures or magnetic fields that may exist in the design. Furthermore, the position tracking method has very low jitter and the lowest latency of all tracking types. Unlike optical tracking systems, the position tracking system has no problem with visual occlusion of the tracked object, specifically the fingertip.

B. Force Measurement Module

Piezoresistive sensors or, simply, FSR are used to measure the contact force between the fingertip and the object and the force between the glove and the user's hand. The FSRs on the SAFE Glove are robust polymer thick film devices that exhibit a decrease in resistance with increase in force applied to the surface of the sensor. They are of high performance but low cost. The force sensitivity is optimized for use for human touch control and the actuation force is as low as 0.1 N with a sensitivity range of 10 N (maximum force can be modified in custom sensors).

C. Free Motion Recording During Demonstration

The capability of free motion is a basic evaluation criterion of haptic devices [29]. In the free motion mode (i.e., the state with zero force input), the haptic glove's user should be able move his/her fingers freely without feeling resistance or inertia from the glove. The resistance and inertia should be compensated for via a real-time control algorithm based on the force and position sensors input. We determined that the force between the glove and the human finger should be as small as possible in free motion. If the device is controlled and the force set to be zero, the glove will follow the movement of the user's fingers. Thus, the user cannot feel the resistance force.

D. 3D GUI Design and Interaction Algorithm

The main disadvantage of the desktop LCD screen is its 2D display, which lacks depth visualization information. Thus, the head-mounted display (HMD) (WRAP 920, made by Vuzix Corp.) was adapted into our rehabilitation application as an interface display. This device has 2 LCD screens with a resolution of 640×480 pixels and an update rate of 60 Hz, equivalent to a 67-in screen as viewed from 3 m.

The brain uses the horizontal shift in image position registered by the two eyes to measure depth, or the distance from the viewer to the object presented in the scene. Therefore, stereographic displays need to output two slightly shifted images. Specifically, the two displays each present an image to the corresponding eye. The HMD uses special optics placed between the HMD image screens and the user's eyes in order to allow the eyes to focus at such short distance without tiring.

The user interface software was adopted from CHAI 3D [30], which is a scene graph API written in C++ language. Due to its lightweight and compact functionality, CHAI 3D is designed for

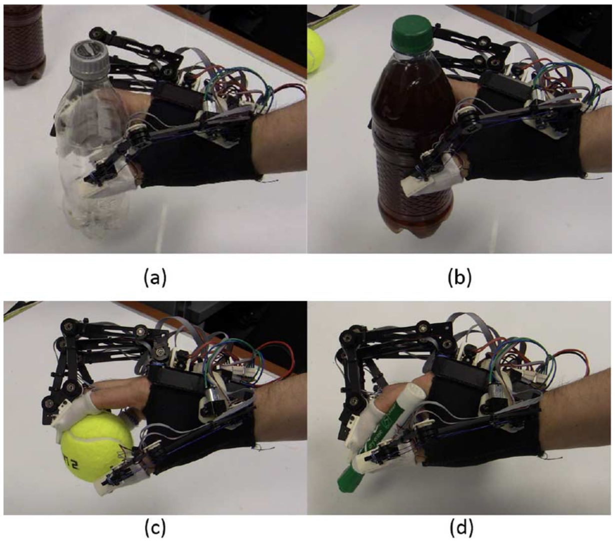

Fig. 4. Demonstration experiments for grasping different objects with the third generation SAFE Glove system. (a) an empty bottle; (b) a bottle of liquid; (c) a tennis ball; (d) a marker pen.

academic and research use. Equipped with an OpenGL graphics library and Open Dynamics Engine (ODE) module, CHAI 3D is ideal for our 3D visualization of the hand rehabilitation application with both kinematics and dynamics simulations since it mainly focuses on haptics devices combined with graphics. All physical interactions between the virtual hand and the virtual objects are computed by the ODE module. The user interface software computes the interaction forces between the virtual hand and the objects; the resulting forces are then transferred to the ODE engine to update the dynamic configuration of each object and virtual hand in real time. Gravity can be either enabled or disabled by the user.

As the user manipulates the glove through a virtual scene, the interface software rapidly performs a number of tasks that ensure realistic feedback and timely reaction to the interaction events. The main algorithmic requirements can be divided into five steps and are summarized as follows.

1. Scene setup:
   - Import virtual objects and the virtual hand which were made in the 3D CAD software (Creo Parametric).
   - Set object properties such as materials, color, stiffness friction, etc.
   - Create a stereo camera to generate two display images, one for each eye.
   - Initiate the five-finger glove through serial port.
2. Finger movement acquisition and update:
   The hand motions (includes the position and orientation of the palm and the rotation of each finger joint) are measured and used to update the virtual hand within the virtual scene.
3. Collision detection and force calculation:
   The software determines whether, and to what extent, the virtual hand is interacting with any object in the virtual world. That is, has the virtual hand "touched" or "penetrated" any object in the scene? If collision does happen, the contact/reaction force is calculated based on the dynamic property of each object.

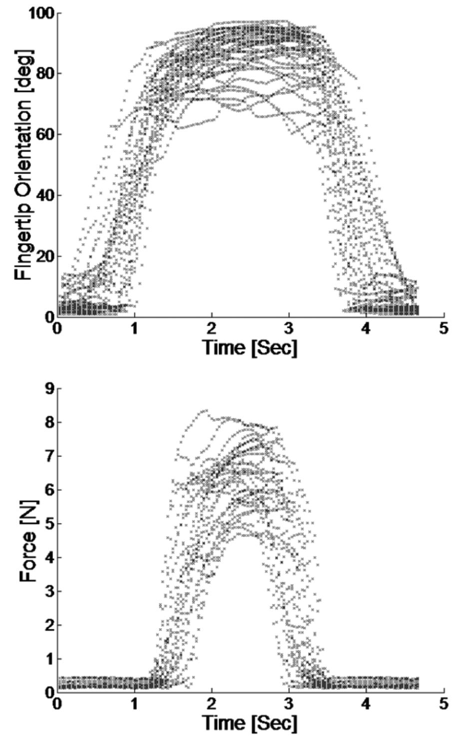

Fig. 5. Demonstration grasping motion and force reading from the index finger in grasping a bottle of water test: (top) fingertip motion; (bottom) fingertip force.

4. Haptic Feedback
   In this step, the appropriate haptic force is sent to the glove to display to the user. If no collision was detected in the previous step, zero force is displayed on the finger, which means the glove is controlled to follow the user's finger movement.
5. Scene update:
   The positions or movements of objects within the virtual world are updated according to the interaction with the glove, for example, the object trajectory or shape is modified.

Step 1 can be considered as the initial setup of the program. Steps 2–5 are repeated as a loop to realize the update of the GUI.

IV. Experiments

A. Demonstration Experiment

The demonstration experiment is to record finger movements and force during grip patterns. Twelve volunteers, between the ages of 20–69 years, and with normal, pain-free function in both hands, participated in this test.

The testing session consisted of grasping and lifting an empty bottle, grasping and lifting a bottle full of liquid (500 grams), squeezing a tennis ball, and holding a marker pen as if preparing to write (Fig. 4). After getting used to wearing the SAFE Glove, the participants were asked to repeat each activity three times in about 5–10 s. In this test, the glove was controlled to follow the finger movement by minimizing the force (measured by Fa as shown in Fig. 2) between the finger and the glove throughout the motion As a representative example of the test results, the demonstration grasping force (Measured

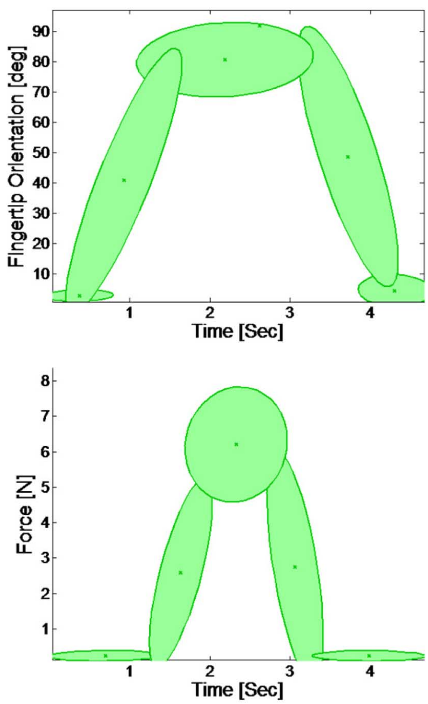

Fig. 6. GMM model result: (top) motion; (bottom) force.

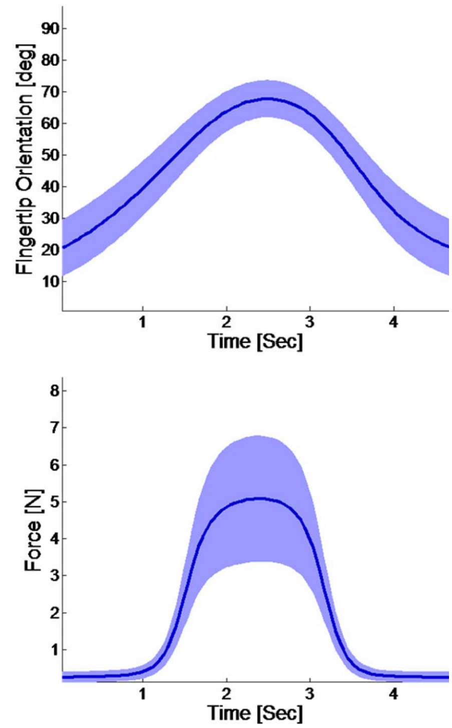

Fig. 7. Generated force trajectory with GMR: (top) motion; (bottom) force.

by Fb as shown in Fig. 2) reading from the index finger in grasping a bottle of water is shown in Fig. 5. The GMM model of the force and motion dataset during 36 trials (12 users, three trials per person) of grasping demonstration is shown in Fig. 6. The number of mixture components is selected to be three, because the grasping process is naturally segmented into three phases of movement: grasp the object, lift and place back the object, and release the object. Due to the DTW, as shown in Fig. 5, variance between movement phases is much larger than the variance between different trials and that's why the GMM is differentiating between phases of movement, not between trials. Another benefit of the DTW is that the demonstration procedure does not need to time experimental phases, which enable much more free motion for the users. Fig. 7 shows the generated GMR trajectories, which work as input signal to the controller module of the SAFE Glove.

B. Actuating a Passive (Wooden) Hand Experiment

In this experiment the SAFE Glove is attached to a wooden hand (Fig. 8) that cannot produce any force by itself.

Fig. 9 displays snapshots of the wooden hand executing manipulation tasks. Due to design limits, the wooden hand cannot pick up a pen. The empty bottle results are similar to those for the full bottle. Thus these two are not shown here. In Fig. 10 the actual motion and force trajectories of the glove applied for grasping different objects can be seen. In the first stage, the glove rotates the wooden hand until the fingers contact the object, and the contact force remains at a small value (almost zero). Then the wooden hand grasps and picks up the object while the controller generates appropriate contact forces. In the last stage, the wooden hand releases the object.

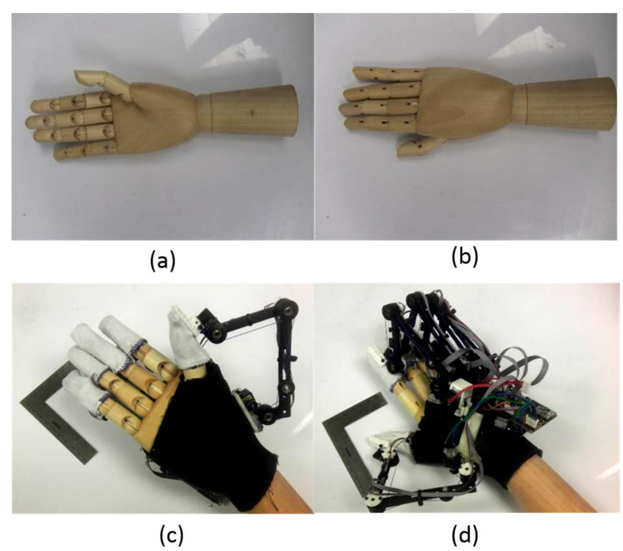

Fig. 8. Wooden hand and the glove system (the third generation) mounted to the wooden hand. (a)–(b) front and back views of the wooden hand; (c)–(d) front and back views of the glove system mounted on the wooden hand.

C. Assisting Hand Motion Experiments

The purpose of this experiment was to generate the movement patterns shown in Fig. 4 in a playback fashion to assist a "weakened" hand in order to accomplish these movements. Since the subjects had healthy hands, he/she was asked to passively follow the glove movement without applying any active force. The glove was programmed to actively drive the user's fingers to follow the force trajectory from the learned data. Fig. 11 shows snapshots of assisting hand motion for grasping different objects. The index finger motion and force results during this test

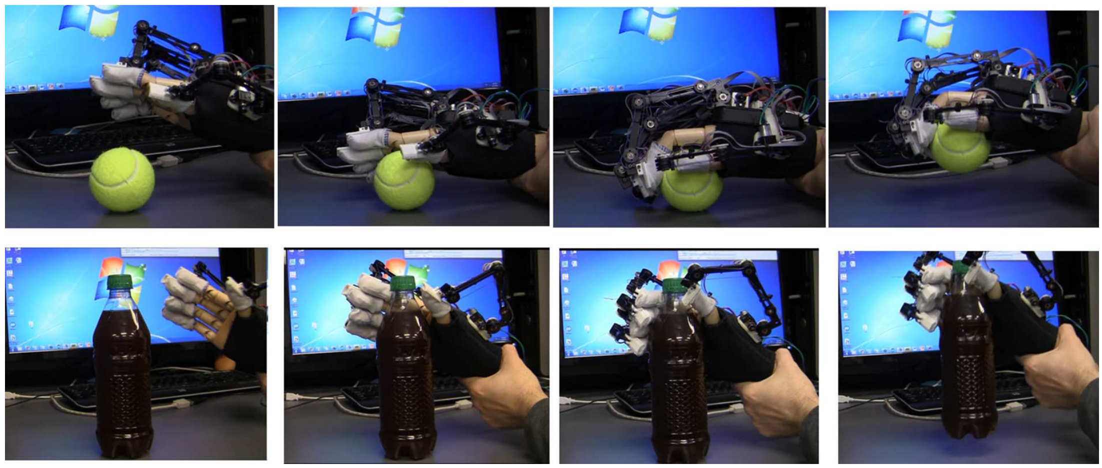

Fig. 9. Snapshots of the wooden hand executing manipulation tasks. Top row: the wooden hand approached the tennis ball (assisted by the author), grasped it, and lifted it (author) from the table. Bottom row: the wooden hand was controlled to grasp a bottle of liquid. Procedure setting similar to the tennis ball grasping.

are shown in Fig. 10. The other fingers' motions have similar results.

Fig. 12 displays similar pattern of fingertip trajectories and contact force between the finger and object, which demonstrate that the glove was controlled smoothly and effectively. The force between the finger and the glove [according to Fig. 12 (middle)] that is used to drive the hand motion is always larger than the force between the finger and the object [according to Fig. 12 (bottom)]. These experimental results validate that the SAFE Glove is capable of reliably recording and assisting hand function in some daily grasping movements.

D. Virtual Reality Rehabilitation Experiments

On the host unit, a 3D virtual world software was programmed with C++ to show the hand kinematics in real-time. The interaction software tracks the position of a virtual representation of the user's hand within the digital scene and calculates and transmits appropriate haptic feedback data to the physical glove for display to the user. The relation between the software and the haptic glove is simple: the glove sends the hand position data to the software, and the software sends the virtual contact force (between the virtual hand and virtual object) to the glove.

After getting the hand position data from the glove, the software, which is running on a PC, was programmed to show the hand kinematics in real-time based on forward kinematics. When the software detects collisions between the Haptic Interface Point (HIP) and the virtual objects, the Open Dynamics Engine (ODE) calculates the contact force and sends this force information to the glove. In our application, there are five HIPs at five finger tips of the virtual hand.

On the glove end, the low-level controller activates the glove mechanism to apply the received force information to the fingertip. Thus, the user could feel the virtual object. Meanwhile, the glove keeps measuring and sending the hand position wirelessly to the 3D interface software.

After wearing the SAFE glove, through the interface, the user could watch and manipulate the virtual hand and objects

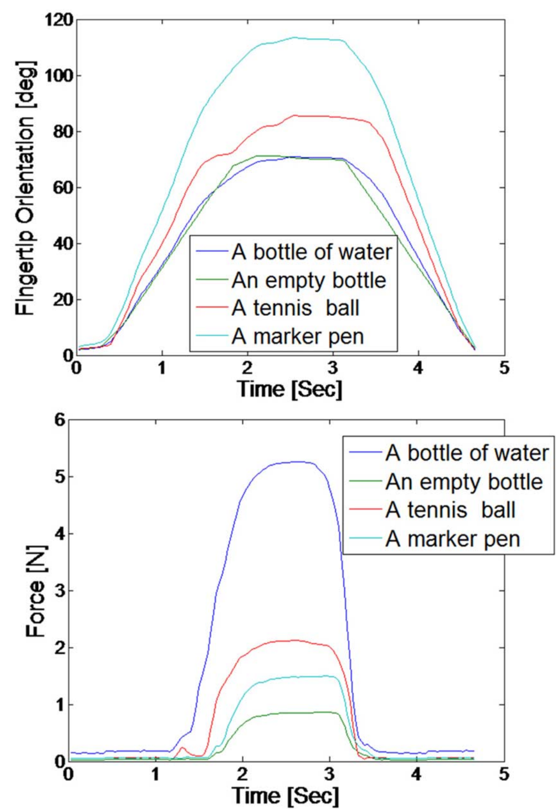

Fig. 10. Force and motion results recorded from the glove grasping different objects. (top): motion results; (bottom): force results.

in HMD in 3D in real-time. As shown in Fig. 13, the user could control the virtual hand to grasp the tool and feel the contact force at the fingertips through the SAFE Glove and the interface program. Virtual hands controlled by the glove will follow the position of the user's fingers in real-time.

The application of the SAFE Glove in VR may have numerous medical applications. These include safely improving medical training, since any training movement errors would be on the virtual objects rather than on real patients.

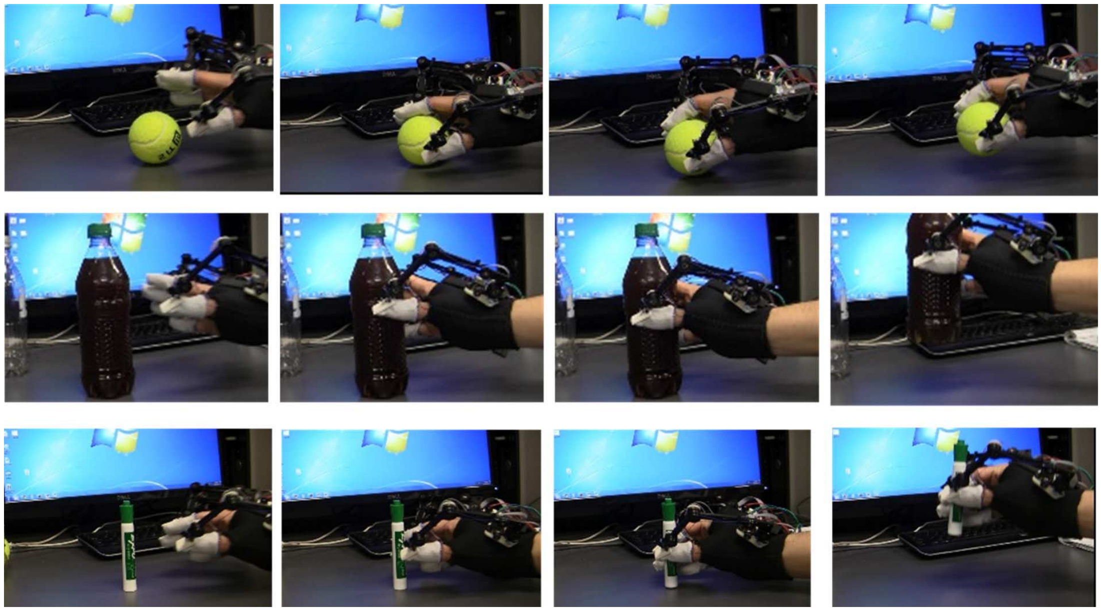

Fig. 11. Snapshots of assisting hand motion experiments. Top row: the user's hand approaches the tennis ball, grasps it with the help of the glove, and lifts it from the table. Middle row: the user's hand is assisted to grasp a bottle of water. The procedure setting is similar to the tennis ball grasping. Bottom row: the user's hand is assisted to grasp a marker pen.

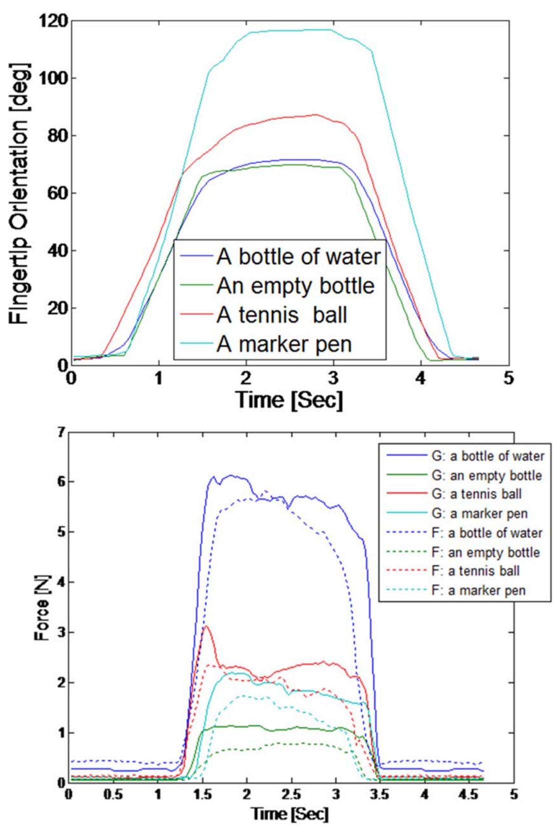

Fig. 12. Index finger motion and force during assisting grasping of different objects: (top) Fingertip trajectories; (bottom—solid line) force between the finger and the glove; (bottom—dotted line) force between the finger and the object.

V. Conclusions and Future Work

This paper presents an application of the SAFE glove in the field of rehabilitation. The authors have proposed a new grasping rehabilitation learning system that is designed to gather kinematic and force information of healthy hands and to playback the motion to assist users with hand disabilities in common hand-grasping movements, such as grasping a bottle of water. The fingertip forces as measured by the SAFE Glove are modeled with GMM based machine learning approach. The learned force distributions are then used to generate fingertip force trajectories with a GMR approach. Instead of defining a grasping force, force trajectories are used to control the SAFE Glove to actuate/assist a wooden hand/user to carry out a learned grasping task. The scope of these experiments was limited to experimenting on a wooden hand and healthy hands. To demonstrate the glove's ability to manipulate the hand, experiments with the glove fitted on a wooden hand to grasp various objects were performed. To further prove that hands can safely be driven solely by the haptic mechanism, force sensor readings placed between each finger and the mechanism are plotted. The experimental results show the future potential of the proposed system in rehabilitation therapy.

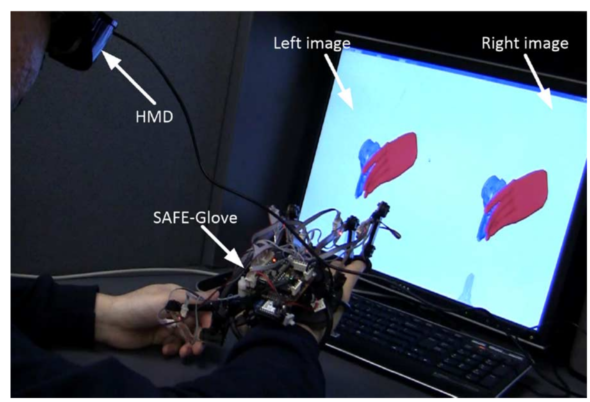

Fig. 13. Virtual reality experiment with the glove system.

A. Limitations of the Device

The movement of the human hand is extraordinarily complex, and normal movement in everyday activities such as typing, tying one's shoes, buttoning a shirt, or playing piano show just how complex hand movement can be. In this paper, some aspects of hand function have been ignored to make the design practical. For example, the proposed device does not have the function to record and reproduce the abduction/adduction movement of the fingers, though the device can accommodate finger abduction and adduction. Similarly, the device can accommodate the palmar arch, but with no means of recording or reproducing it.

Moreover, since the device mounts 50 mm above the dorsum of the hand, it would be difficult to perform some basic hand functions such as retrieving a key ring from a pocket or purse, shuffling cards, or measuring ingredients wearing the device.

The device uses a single driver to replace the finger flexors and extensors and the interossei in its powered orthosis mode. Thus, it can only assist the user to open or close each finger, but not reproduce the normal finger movement perfectly. In terms of speed of motion, the device can move from full flexion to full extension in 1 s, which is still much slower than the fastest movement normally possible by the fingers.

In addition to the speed limitations, the device is not able to produce sufficient forces for power grip. A typical cylindrical grip, for an adult male, is over 400 N. Normal pinch strength is around 60 N. Suitable light weight motors able to generate such high strength for the power grip function are not currently available.

The device cannot produce all movement functions of a normal hand, adds some weight and bulk to the hand, and moves a little more slowly. However, it has the potential of providing a very good solution by concurrently overcoming some of the most important problems that existing systems cannot provide.

B. Future Work

1) 3D Tracking of the Hand-Glove System: The current SAFE Glove only measures the finger position. Future work may extend to measuring the whole hand's position and orientation by adding a 3D tracking system to the glove to facilitate this measurement so that the system can be used for rehabilitation applications or be integrated with virtual reality environments.

2) Sensing the Hand's Intention to Move: For rehabilitation or assisting hand motion applications, accurate sensing of the user's intended motion is one key concern. In the current design, the glove measures the contact force between the fingertip and the glove mechanism for detection of motion intention. However, this method may not be applicable for patients whose fingers cannot move.

Surface electromyography (sEMG) can be used to noninvasively estimate the level of muscle activation. Controlling the haptic glove with the EMG signal has the fast response advantage since there is no time delay compared to the contact force measurement method. Studies have shown that the torque developed by the fingers can be estimated from the sEMG signal from the forearm muscles.

However, the sEMG signal may be very low when muscles are very weak, so the electrodes need to be carefully placed on the skin to stabilize and minimize the contact resistance. In addition, the skin humidity and electrode location may affect the measurement results greatly.

Another potential method to measure the user's intended motion is to adapt a disturbance observer [31]. The classical conventional disturbance observer is used to compensate the disturbances force between the hand and exoskeleton, which may also indicate the user's movement intention. With the combination of velocity observer, a force observer and a disturbance observer, the user's movement intention may be effectively predicted.

3) On-Line Learning Algorithm: During the demonstration procedure, thanks to the DTW technique, the users have lots of freedom, no matter if it's slower or faster, they can finish the grasping task at any speed they like. But this free motion does not apply to the rehabilitation users because they are forced to grasp the object by following a common trajectory at a specific speed. Thus, another possible future work is to employ an on-line learning algorithm to dynamically adjust the grasping speed and the force trajectory.

4) Multiple Device Cooperation: This objective seeks to study the actuation scheduling architecture that enables a cooperation of left and right SAFE Gloves in order to accomplish a desired task. For example, synchronizing the motion of left and right SAFE Gloves to assist both hands when using a fork and knife at the same time.

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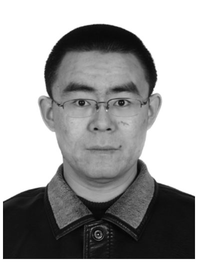

Zhou Ma (S'10) received the M.S. degree in electrical engineering from the University of Science and Technology, Beijing, China, in 2009, and the Ph.D. degree from the George Washington University, Washington, DC under the supervision and guidance of Prof. Pinhas Ben-Tzvi.

He is currently with US Med Innovations Co. His current research interests include basic and applied research in robotics and mechatronics, and involve investigations in haptics glove design, simulation and optimization, with applications to rehabilitation.

Pinhas Ben-Tzvi (S'02–M'08–SM'12) received the B.S. degree (*summa cum laude*) in mechanical engineering from the Technion—Israel Institute of Technology, Haifa, Israel, and the M.S. and Ph.D. degrees in mechanical engineering from the University of Toronto, Toronto, ON, Canada.

He is currently an Associate Professor of Mechanical Engineering and the founding Director of the Robotics and Mechatronics Laboratory at Virginia Tech, Blacksburg, VA, USA. Before joining the University of Toronto in 2002, he was an R&D Engineer with General Electric Medical Systems Company, developing medical diagnostic robotic and mechatronic systems. His current research interests include robotics and autonomous systems, mechatronics, dynamic systems and control, mechanism design and system integration, and sensing and actuation. Applications include robust dynamic stabilization and agile maneuvering of mobile robots using intelligent biomimetic robotic tails; autonomous mobile robot mobility and manipulation and modular and reconfigurable mobile robotics for search and rescue, environment monitoring, and defense; advanced devices and robotic systems for medicine; haptics devices and exoskeletons for robot control and rehabilitation; and novel sensors and actuators for biomedical applications. He has authored and co-authored more than 75 peer-reviewed journal articles and refereed papers in conference proceedings and is the inventor of five U.S. patents and a Canadian patent.

Dr. Ben-Tzvi is the recipient of the 2013 GW SEAS Outstanding Young Researcher Award and the GW SEAS Outstanding Young Teacher Award, as well as several other honors and awards. He is a member of the American Society of Mechanical Engineers (ASME).

Jerome Danoff received a Physical Therapy degree from the University of Maryland, Baltimore, MD, USA, the B.S. degree in engineering science from Johns Hopkins University, Baltimore, MD, USA, the M.S. degree in aerospace engineering from Pennsylvania State University, State College, PA, USA, the Ph.D. degree in kinesiology from the University of Maryland, College Park, MD, USA.

He has been teaching in the areas of anatomy, physiology, kinesiology, biomechanics, modalities, statistics, and research design for over 30 years and has been on the faculties of the University of Maryland, Howard University, and The George Washington University. He has also served as adjunct faculty at Boston and Shenandoah Universities. In addition to teaching, he has been actively involved in research and has served as a research consultant to the Department of Rehabilitation Medicine at the National Institutes of Health and as Chief of Physical Therapy in the Clinical Center, NIH. His research has included movement analysis (normal and abnormal), cancer (treatment outcomes, modalities), HIV (functional capabilities in infants, children, and adolescents), stroke and cardiac problems (functional assessment, performance), and acupuncture. He has authored or co-authored more than 50 peer-reviewed publications.

Dr. Danoff is a member of the American College of Sports Medicine and the American Physical Therapy Association. He is a licensed Physical Therapist and is active in the Orthopedic, Clinical Electrophysiology, and Research Sections of the APTA. He also is a manuscript reviewer for several professional journals.