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Sensing and Force-Feedback Exoskeleton Robotic (SAFER) Glove Mechanism for Hand Rehabilitation

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ABSTRACT

This paper presents the design and application of the SAFER glove in the field of hand rehabilitation. The authors present preliminary results on a new hand grasping rehabilitation learning system that is designed to gather kinematic and force information of the human hand and to playback the motion to assist a user in common hand grasping movements, such as grasping a bottle of water. The fingertip contact forces during grasping have been measured by the SAFER Glove from 12 subjects. The measured fingertip contact forces were modeled with Gaussian Mixture Model (GMM) based on machine learning approach. The learned force distributions were then used to generate fingertip force trajectories with a Gaussian Mixture Regression (GMR) method. To demonstrate the glove's potential to manipulate the hand, experiments with the glove fitted on a wooden hand to grasp various objects were performed. Instead of defining a grasping force, contact force trajectories were used to control the SAFER Glove to actuate/assist this hand while carrying out a learned grasping task. To prove that the hand can be driven safely by the haptic mechanism, force sensor readings placed between each finger and the mechanism have been plotted. The experimental results show the potential of the proposed system in future hand rehabilitation therapy.

1 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 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]. A rough breakdown of major types of haptic gloves could be summarized as 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 range of motion for the person wearing the glove 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 devices due to the user's fatigue, which can lead to hand and arm pain. 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. Other work in hand-rehabilitation devices also includes soft gloves with cable and fluidic actuators [30-32].

Previously, we have presented the design of a body-based robotic haptic exoskeleton device (SAFER Glove) to measure the user's hand motion and assist hand motion while remaining portable and lightweight [22, 29]. 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 that has the ability to learn patterns of fingertip motion and contact force data so that the glove can then assist the 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 preliminarily evaluate the proposed hand rehabilitation system. Finally, Section V provides the conclusions and future work. Experiments

2 THE PROPOSED REHABILITATION LEARNING SYSTEM

2.1 Overview of the Rehabilitation System

A preliminary grasping learning and rehabilitation system is proposed that is capable of measuring and learning from human grasping and providing rehabilitation function to the user. The system overview is shown in Fig. 1. It includes four components: the demonstration procedure, the SAFER Glove system, the machine learning algorithm and a 3D GUI program, and the rehabilitation/assistive engineering procedure. Among them, the SAFER Glove and the learning algorithm are the center pieces. The SAFER Glove measures both motion and contact force information in the grasping procedure demonstration. Then the captured motion and force data are used to train a Gaussian Mixture Model (GMM) [23], which represents the joint distribution of the data. The learned motion and force information representing skill is then mapped to the SAFER 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.

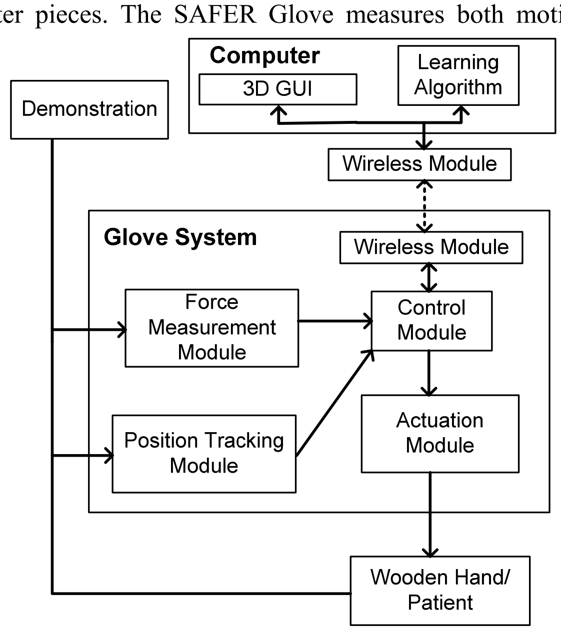


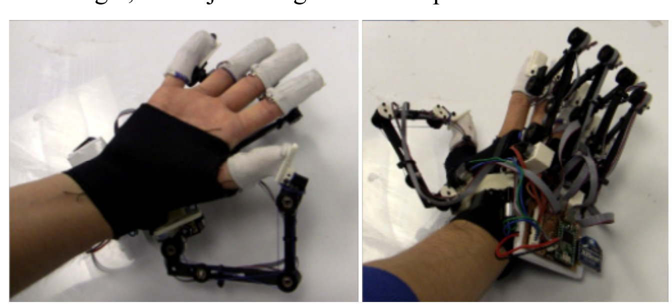
Figure 1. Overview of the rehabilitation learning system.

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 [24]. 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.

2.2 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 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 display actuators. This design minimizes the size and weight and maximizes the workspace and force output range of the glove. Since all necessary components are light and contained inside the glove, the user can move each finger freely without being tethered or feeling fatigued.

The whole system, including the glove skeleton and mechanism, battery, actuator unit, control system and wireless module, weighs 430 g. Besides being lightweight, it is also a portable, wireless and self-contained actuator system. On each finger, three rotational sensors provide accurate joint angle data to calculate the finger position. Force sensors and shunt circuit for measuring the motor current are also adopted. Thus, for each finger, three joint angles and torque/force measurements



(a) (b)

Figure 2. SAFER Glove prototype worn on a right hand.

are available in a highly compact package for feedback control and for data collection with no need for an additional glove or measurement equipment.

The primary advantages of the SAFER Glove are as follows. First, it is light-weight, 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 SAFER 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.

2.3 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 SAFER 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.

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; $\xi_{j,f} \in \Re^3$ is the force vector. The data set can be represented by a probabilistic model, the Gaussian Mixture Model (GMM), which is a mixture of K Gaussian distributions.

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

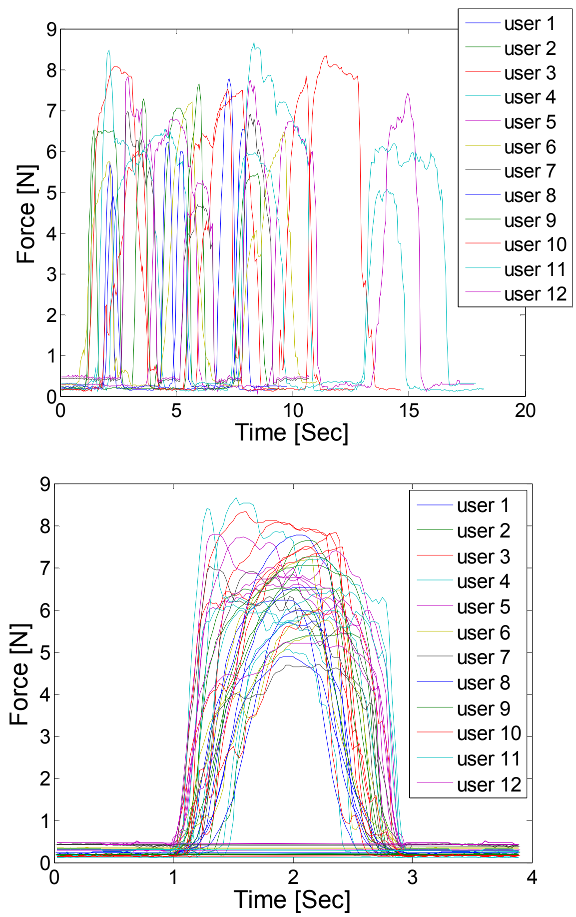


Figure 3. DTW result for index force data. (top): raw data; (bottom): DTW result.

2.4 Learning Result Mapping to a Passive (Wooden) Hand

Given a joint probability distribution $p(\xi_t, \xi_m)$ and $p(\xi_t, \xi_f)$ of the dataset modeled by a GMM, Gaussian Mixture Regression (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 is controlled to follow those motion and force trajectories generating the grasping patterns in playback fashion to actuate/assist a wooden (or subject's) hand to accomplish these movements. The glove adapts a hybrid motion and force controller to ensure the fingers of the user's hand keep contact with the object with a certain force, based on the GMR. In this research, only the normal force is controlled due to the limitation of the Force Sensitive Resistor (FSR) sensor used.

2.5 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 both to 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 [25, 26].

3 SYSTEM IMPLEMENTATION

3.1 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 3 miniature plastic precision potentiometers with a precision of 0.09 degree (12 bit AD converter). Wires from each encoder 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 encoder sensors.

Using encoders 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 encoder sensors 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 encoder tracking method has very low jitter and the lowest latency of all tracking types. Unlike optical tracking systems, the encoder tracking system has no problem with visual occlusion of the tracked object, specifically the fingertip.

3.2 Force Measurement Module

Piezoresistive sensors or, simply, force sensing resistors (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 SAFER 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 0.1N with a sensitivity range of 10N (maximum force can be modified in custom sensors).

3.3 Free Motion Recording During Demonstration

The capability of free motion is a basic evaluation criterion of haptic devices [27]. 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 zero, the glove will follow the movement of the user's fingers. Thus, the user cannot feel the resistance force.

3.4 3D GUI Design

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 640x480 pixels and an update rate of 60 Hz, equivalent to a 67-inch 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 [28], which is a scene graph API written in C++ language. Due to its lightweight and compact functionality, CHAI 3D is designed for 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 since it mainly focuses on haptics devices combined with graphics.

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 5 steps and are summarized as follows:

1. Scene setup:
   - Import virtual objects and the virtual hand which was 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.

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.

4 EXPERIMENTS: SENSING THE HAND MOTION

4.1 Demonstration Experiment

The demonstration experiment is to record finger movements and force during grip patterns. Twelve volunteers, between the ages of 20 to 69 years, and with normal, pain-free hand function, 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 SAFER Glove, the participants were asked to repeat each activity three times in about 5–10 seconds. In this test, the glove was controlled to follow the finger movement by minimizing the force between the finger and the glove throughout the motion. As a representative example of the test results, the demonstration grasping force reading from the index finger in grasping a bottle of liquid is shown in Fig. 5. The GMM model of the force and motion dataset during 36 trials (12 users, 3 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 naturally has three states: grasp the object, lift and place back the object, and release the object. Fig. 7 shows the generated GMR trajectories, which work as input signal to the controller module of the SAFER Glove.

4.2 Actuating a Passive (Wooden) Hand Experiment

In this experiment, the SAFER Glove is attached to a passive 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 In Fig. 9 s 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 force. In the last stage, the wooden hand releases the object.

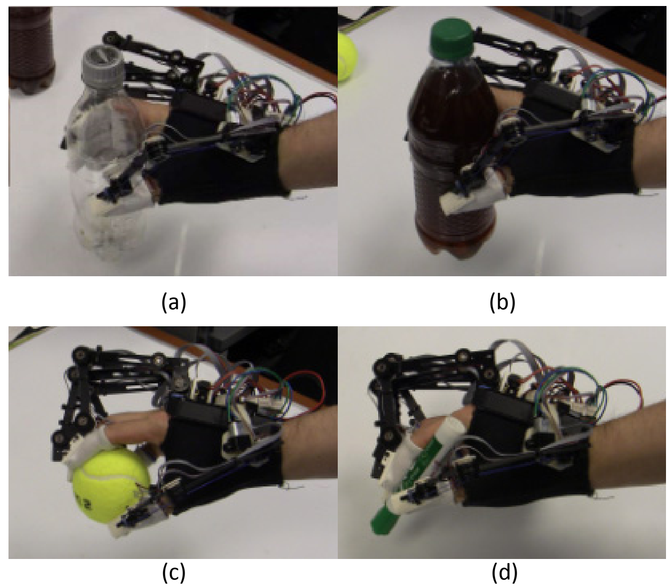


Figure 4. Demonstration experiments for grasping different objects with the third generation SAFER Glove system. (a) an empty bottle; (b) a bottle of liquid; (c) a tennis ball; (d) a marker pen.

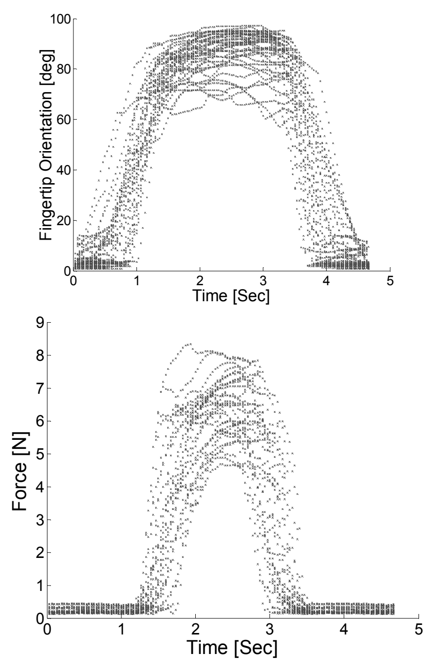


Figure 5. Demonstration grasping motion and force reading from the index finger in grasping a bottle of water test: (top) fingertip motion; (bottom) fingertip force.

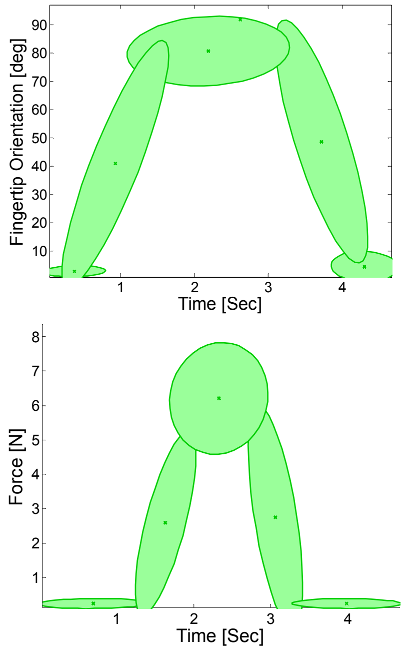


Figure 6. The GMM model result: (top) motion; (bottom) force.

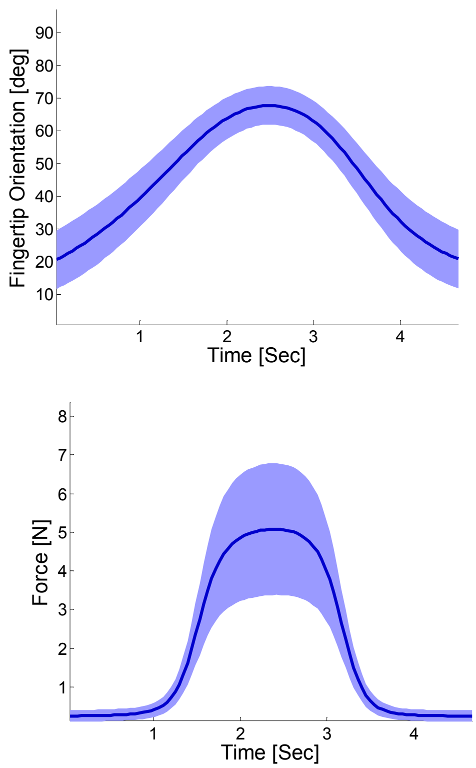


Figure 7. Generated force trajectory with GMR: (top) motion; (bottom) force.

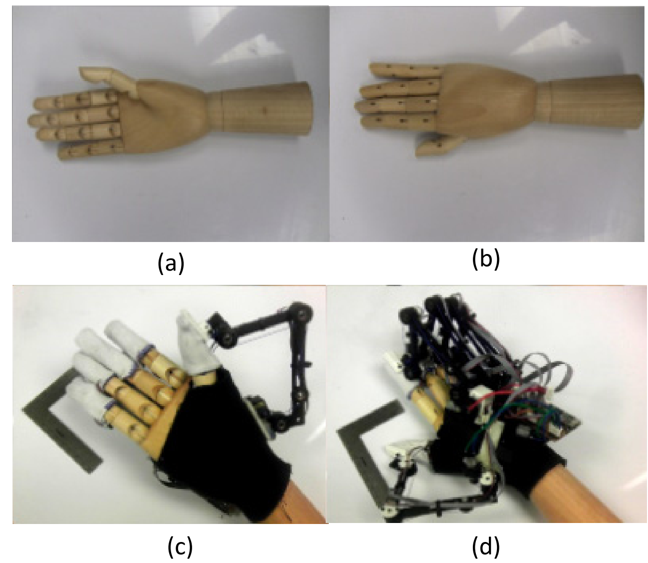


Figure 8. A wooden hand and the glove system (the third generation) mounted to the wooden hand. (a)-(b) the front and back views of the wooden hand; (c)-(d) the front and back views of the glove system mounted on the wooden hand.

5 CONCLUSIONS

This paper presents an application of the SAFER glove in the field of hand rehabilitation. The authors have proposed a new grasping - learning system that is designed to gather kinematic and force information of normally functioning hands and to playback these motions to assist grasping movements, such as grasping a bottle of water, for users with weak or impaired hands. The fingertip forces, modeled with GMM based machine learning approach, are measured by the SAFER Glove. The learned force distributions are then used to generate fingertip force trajectories with a GMR approach. For safety, and to demonstrate the glove's ability to manipulate the hand, the glove was fitted on a wooden hand and various objects were grasped. Instead of defining a grasping force, force trajectories were used to control the SAFER Glove and to actuate/assist finger movements. To further establish that the hand can safely be driven solely by this haptic mechanism, force sensor readings placed between each finger and the mechanism are plotted. These experimental results demonstrate that this proposed system has potential in future hand rehabilitation therapy.

Future work will focus on improving the learning system and performing experiments involving the use of the glove on healthy hands. In addition, future work will include: (1) 3D tracking of the hand-glove system; (2) sensing the hand's intention to move as a means to autonomously activate the glove mechanism; and (3) perform "multiple device cooperation" such as synchronizing the motion of left and right SAFER Gloves to assist both hands to use a fork and knife at the same time.

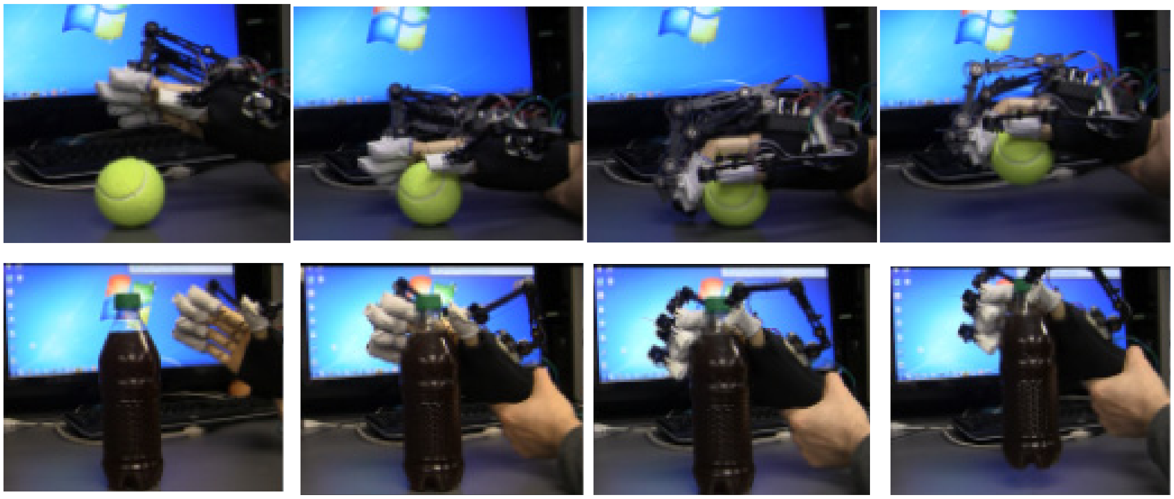


Figure 9: Wooden hand executing manipulation tasks. Top row: the wooden hand approached the tennis ball (by the author), grasped it, and lifted it (by the author) from the table. Bottom row: the wooden hand was controlled to grasp a bottle of water. The whole procedure setting was similar to the tennis ball grasping.

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