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Abstract

Without the sense of touch, amputees with prosthetic hands can have difficulty holding and manipulating objects, especially when a task requires some degree of skill and tactile feedback to perform. To equip prosthetic hand users with touch sensing and tactile feedback, researchers have been experimenting with various types of force and/or tactile sensors together with various methods for delivering the tactile information to the brain. Although some success has been achieved recently with force sensors and implanted electrodes, these systems are expensive, surgically invasive and can represent an infection risk where cables emerge through the skin. Also, non-invasive tactile feedback methods involving temperature, vibrations or electro-mechanical force feedbacks, can be somewhat awkward and ineffective due to being cumbersome or unable to deliver appropriate sensations. To address some of these issues we have been developing an electro-tactile feedback system for prosthetic hands. Our proposed system is comprised of force sensors that can be placed almost anywhere on a prosthetic hand, and TENS electrodes that can be placed on the wearer's arm. Our system is inexpensive, multi-channel and easily fitted to existing prosthetic hands. Experimental results are provided that show how this form of tactile feedback can enable a user to feel various objects touched or gripped with a robotic humanoid hand. Keywords: prosthetic hand, electro-tactile feedback

Keywords

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Electro-Tactile Feedback System for a Prosthetic Hand

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Abstract. Without the sense of touch, amputees with prosthetic hands can have difficulty holding and manipulating objects, especially when a task requires some degree of skill and tactile feedback to perform. To equip prosthetic hand users with touch sensing and tactile feedback, researchers have been experimenting with various types of force and/or tactile sensors together with various methods for delivering the tactile information to the brain. Although some success has been achieved recently with force sensors and implanted electrodes, these systems are expensive, surgically invasive and can represent an infection risk where cables emerge through the skin. Also, non-invasive tactile feedback methods involving temperature, vibrations or electro-mechanical force feedbacks, can be somewhat awkward and ineffective due to being cumbersome or unable to deliver appropriate sensations. To address some of these issues we have been developing an electro-tactile feedback system for prosthetic hands. Our proposed system is comprised of force sensors that can be placed almost anywhere on a prosthetic hand, and TENS electrodes that can be placed on the wearer's arm. Our system is inexpensive, multi-channel and easily fitted to existing prosthetic hands. Experimental results are provided that show how this form of tactile feedback can enable a user to feel various objects touched or gripped with a robotic humanoid hand.

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1 Introduction

The human hand and associated sensory nerves have evolved over time to provide humans with considerable dexterity for performing object manipulation, see [1]. This level of dexterity requires precise control of hand and finger muscles with feedback from a complex array of sensory nerves within the hands (see [2]). By grasping objects and receiving tactile feedback, humans are able to perceive various properties of an object (e.g. shape, weight, texture) that can facilitate both the manipulation and classification of objects, as explained in [3]. This complexity poses challenging problems toward the development of prosthetic hands and the rehabilitation of amputees who have lost one or both hands.

adfa, p. 1, 2011.

It is estimated worldwide over 3 million amputees are living with the loss one or both hands. Most prosthetic hands available today provide limited control of artificial fingers and no somatic sensory feedback. Consequently, amputees have to rely mainly on visual feedback and careful control when using a prosthetic hand to pick up or manipulate objects. This can make the prosthetic hand feel unnatural, awkward and distracting which can sometimes result in the amputee refusing to use the prosthetic hand, as explained in [4].

To address this problem, we have been experimenting with the development of an electro-tactile feedback system for prosthetic hands. Our proposed system is comprised of resistive film force sensors, that can be placed almost anywhere on the prosthetic hand, and TENS electrodes that can be placed on nearby skin (e.g. upper or lower arm).

Our system is inexpensive, easily fitted to existing robotic or prosthetic hands and capable of delivering multiple channels of stimulus from the fingers and palm of the prosthetic hand. In addition, each channel is capable of producing a variety of sensations by modulating both the frequency and intensity of the signal. We show how this information can assist when gripping and manipulating objects with a robotic or prosthetic hand.

This paper is organized as follows: Section II provides a brief background review of related work. Section III presents the implementation details of our proposed electro-tactile feedback system. Section IV presents some preliminary experimental results that demonstrate how our tactile feedback system can provide useful tactile feedback when gripping and manipulating objects. Section V provides some concluding remarks and a brief overview of future work.

2 Background

Researchers have been investigating various methods for providing force feedback from prosthetic hands. Most feedback systems involve the use of various types of force sensors embedded in a prosthetic hand combined with various methods for delivering the tactile information to the brain, see [5] for a comprehensive review.

Force sensing is generally achieved by using pressure sensitive resistive films, back EMF from finger actuators, or hydraulic fluid within rubber membrane fingertips combined with pressure transducers, see [6].

Interfacing force sensors to the amputee is achieved either by surgically implanting electrodes that stimulate sensory nerves (see [7] and [8]), or through non-invasive feedback methods involving the use of vibrators [9], air pressure [10] or spatially-mapped tactile displays involving pressure, vibration, shear force or temperature, see [11] and [12].

Although some success has been achieved recently with force sensors and implanted electrodes, such systems are expensive, surgically invasive and can pose an infection risk where the cables emerge from the skin. Non-invasive tactile feedback methods involving temperature, vibrations or electro-mechanical force feedbacks have less bandwidth, but have been shown to improve both the use and the sense of ownership of the prosthetic hand by making it feel less like a tool and more like a natural part of the amputee's body. See [13],[14] and [15].

Saunders and Vijayakumar investigated the utilization of vibro-tactile feedback for informing a user of the forces applied by a robotic hand when gripping an object [13]. This involved fitting eight motoric vibrators to the user's arm between the wrist and the elbow. A light gripper force activates the vibrators nearest to the wrist, whereas, a stronger gripper force activates the vibrators nearer to the elbow. They reported that subjects could grip, lift up and put down objects more effectively with this feedback system.

Similar results were achieved by [14] with the development of a higher bandwidth vibration tactor. This was constructed from three DC vibration motors and was able to generate different sensations by using a combination of different frequencies and amplitudes from the vibration motors.

Kim and Colgate also developed a compound 2-DoF tactor which was able to deliver more information from a robotic hand like low and high touch pressure [15]. Due to the size, and to make it more effective, they chose to mount their tactor on the skin of the user's chest.

The main criticism of vibro-tactile feedback systems is their low bandwidth and limitations in reproducing natural touch sensations. To address this issue some researchers have devised prosthetic hand feedback systems that apply forces to the skin rather than vibration. For example, Antfolk et al [16] developed a mechanical force feedback device for delivering force sensations from a prosthetic hand to the wearer. Their proposed system used five servo motors to deliver force information from five pressure sensors mounted on the fingers of the prosthetic hand. A button is fitted to each servo motor to deliver applied pressure to the user's skin on the user's forearm. Similarly, Ajoudani et al, [17] used a combination of DC motors and pulleys to deliver grip-force information from a prosthetic hand to the user by applying pressure to the upper arm.

Even though these force feedback systems can enable the user to distinguish finger pressure or the grip force of a prosthetic hand they are limited in bandwidth and somewhat cumbersome and therefore can restrict movement and cause the prosthetic hand to feel unnatural to the user. To address these issues we have been developing an electro-tactile feedback system for prosthetic hands.

Previously, electro-tactile stimulation systems have been devised for providing substitute visual perception to the blind, e.g. [18] and [19]. Furthermore, [20] and [21] have experimented with multi-electrode electro-tactile feedback to determine its suitability for haptic perception. Their results show that electro-tactile feedback has potential for delivering haptic sensations from devices such as prosthetic hands but the information can be difficult to resolve when too many closely spaced electrodes are used.

To address the low bandwidth of vibro-tactile feedback systems and to improve on previous work with electro-tactile feedback we have developed a versatile configurable multi-channel electro-tactile feedback system. Our proposed system is comprised of adhesive force sensors that can be placed anywhere on a prosthetic hand, and Transcutaneous Electrical Nerve Stimulation (TENS) electrodes that can be placed almost anywhere on the user's skin. Our system is inexpensive and can be easily fitted to existing prosthetic hands or built into new prosthetic hands. Experimental results are provided that show how this form of tactile feedback can enable a user to feel various objects touched or gripped with a robotic artificial hand.

In the following section we provide the implementation details of our proposed electro-tactile feedback system followed with our preliminary experimental results.

3 Prosthetic Hand and Electro-Tactile Feedback

3.1 Overview

Our electro-tactile feedback system is comprised of force sensors, that are placed on the fingers and palm of a prosthetic hand, interface circuits for processing the sensor data and TENS electrodes that are placed on nearby skin. To test our electro-tactile feedback system we fitted the force sensors to a humanoid robotic hand that was interfaced to a data glove. We also implemented a control panel in software on a PC to monitor the sensor data and deliver appropriate pulses to the TENS electrodes fitted to the user's right arm. The robotic hand was manually positioned with the user's right hand and controlled with the user's left hand via the data glove. This arrangement enabled the user to both control the hand and experience feedback from the electro-tactile feedback system.

3.2 Robotic Hand and Tactile Sensors

The robotic hand was comprised of an EH1 Milano series anthropomorphic hand from Prensilia, as shown in figure 1. The EH1 robotic hand is approximately the same size and configuration as an adult male forearm and hand and has six motors and tendons for manipulating the fingers and thumb. Five motors are utilized for bending the five fingers and one is used for abduction/adduction of the thumb making the EH1 robotic hand capable of manipulating and gripping a wide variety of objects.

To provide the EH1 hand with tactile force sensing, we fitted 16 polymer film force sensors to the fingers and palm of the EH1 hand, as shown in figure 2 and figure 3. Each force sensors was custom cut from a FlexiForce FSR408 sensor strip supplied by Interlink Electronics, as shown in figure 2a. To enable wires to be attached to the force sensors, thin copper conductors were inserted and bonded to each sensor, as shown in figure 2b. Figure 2c shows a finger tip with force sensors fitted. Each force sensor has approximately infinite resistance when no force is applied, 50K ohms when light pressure is applied and less than 5K when pressed firmly.

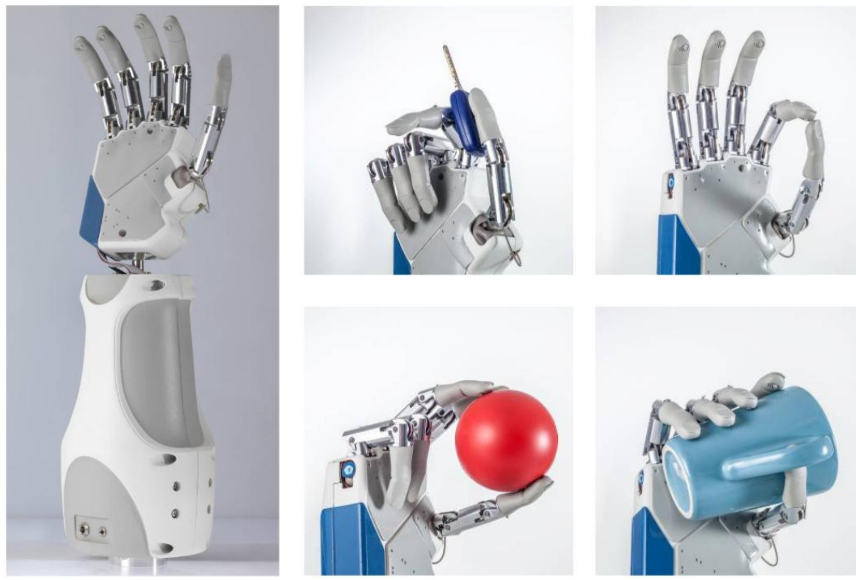
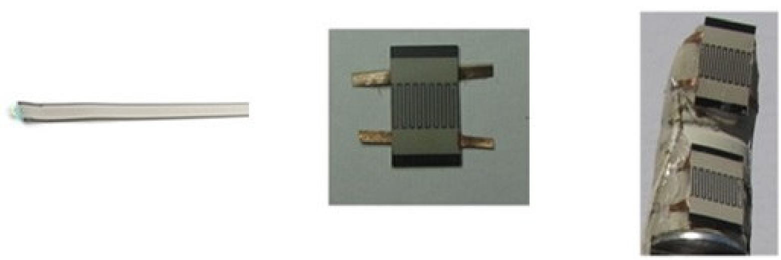


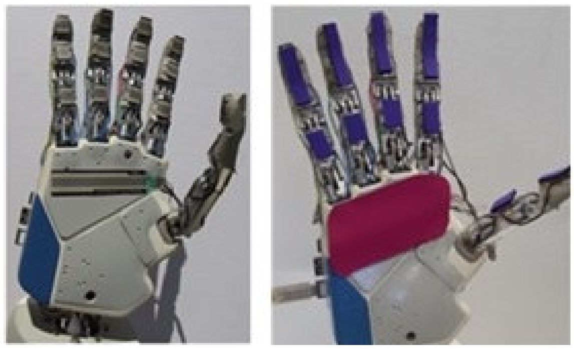
Fig. 1. EH1 Milano Robotic Hand



a b c

Fig. 2. (a). FSR480 force sensor strip. (b). Force sensor cut from FSR480 strip. (c). Cut force sensors mounted on a robotic finger.

Each finger on the EH1 hand was fitted with three force sensors, as shown in figure 3. The sensors were positioned on the distal, middle and proximal phalanges of the fingers, as shown in figure 3a. An additional larger force sensor was fitted to the palm of the hand, see figure 3a. The force sensors were also covered with a thin layer of neoprene to improve the hand's grip and to even out pressure on the sensor surfaces when objects are held, as shown in figure 3b.



a b

Fig. 3. EH1 robotic hand showing: (a) fitted force sensors and (b) neoprene covering.

The force sensors are connected to the analog inputs of a microprocessor control board via voltage divider circuits. The control board samples the analog sensor data 20 times per second and sends it to a PC for further processing and then onto the user as electro-tactile feedback, as explained in the following section.

3.3 Electro-Tactile Feedback System

To deliver the tactile information from the computer to the user, a custom-built wireless TENS electro-tactile feedback system was devised, as shown in figure 4. This feedback system is capable of providing six channels of electrical stimulus to the user's skin with controllable frequency and intensity.

The electro-tactile feedback system consists of a USB transmitter, shown in figure 4a and six TENS receiver units, shown in figure 4b. The transmitter unit transmits data wirelessly from the computer to the receiver units which convert it into electrical pulses that are delivered to electrodes adhered to the user's skin, as shown in figure 4c. A common ground electrode is also adhered to the back of the user's arm. Although the electrodes could be placed almost anywhere on the user's skin, we chose this arrangement to try to approximate sensory hand tactile stimulation.

a b c

Fig. 4. TENS feedback System: (a) Transmiter (b) Receivers (c) Arm with electrodes fitted.

The mapping between the EH1 robotic hand sensors and the electrodes adhered to the user's lower arm is shown in Figure 5. This arrangement allows the user to receive six separate channels of stimulus via sensory nerves in the skin (five for each finger and one for the palm). As the stimulus is relatively mild, painless and adjustable for user comfort, it did not result in any significant muscle contractions during our experiments.

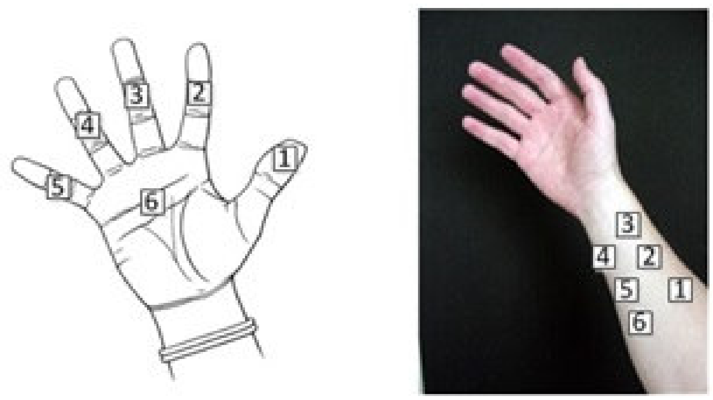


Fig. 5. Mapping between sensor regions and electrodes.

Since each EH1 robotic finger has three force sensors delivering tactile information to one TENS electrode, we mapped three separate stimulation frequencies to each sensor. Namely: distal phalange 100 Hz, middle phalange 60 Hz, proximal phalange 30 Hz and the palm 20 Hz. To avoid confusion, rather than mix the frequencies coming from separate activated sensors on each finger, we chose to deliver only the frequency from the sensor with the most applied force.

The intensity of the pulses delivered to each TENS electrode depends on the amount of force applied to the associated sensors. Again, only the finger sensor with maximum applied force is gated through to the TENS electrode. For simplicity, we divided the intensity into four levels to represent zero, light, medium and high forces.

To adjust the TENS settings and monitor the sensor and feedback data, a graphical user interface was implemented, as shown in figure 6. The user interface has controls for setting the maximum stimulus delivered to each finger and palm as well as indicators for monitoring the raw sensor data and the pulse intensity and frequency sent to the TENS electrodes.

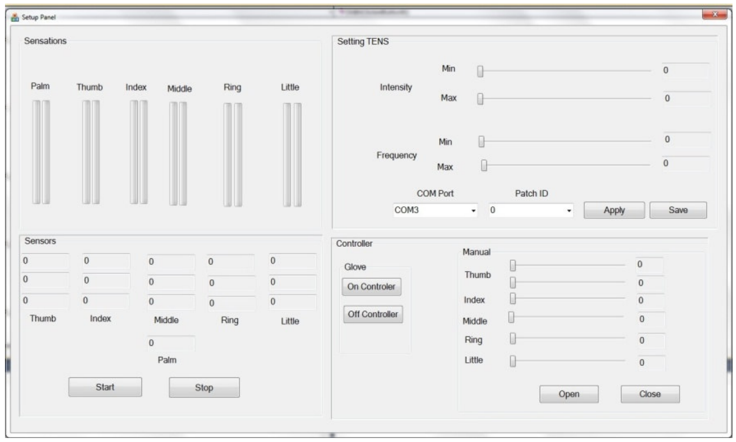


Fig. 6. User Interface

4 Experimental Results

To demonstrate the potential of our electro-tactile feedback system, we fitted a handle to our EH1 robotic hand so that it could be easily held and positioned with the user's right hand. On the left hand of the user, we fitted a P5 data glove linked to the EH1 hand, as shown in figure 7. The electro-tactile feedback electrodes were fitted to the user's right hand, as described in section 3.3. With this arrangement the user could position the EH1 hand with his/her right hand, control the fingers of the EH1 hand with his/her left hand, and experience tactile feedback from the EH1 hand via the TENS electrodes adhered to his/her right arm. Both the grip forces from the EH1 hand's sensors and the electro-tactile feedback delivered to the user via the TENS electrodes could also be observed on the control panel, as shown in figure 8.

Fig. 7. P5 data glove for controlling the robotic hand.

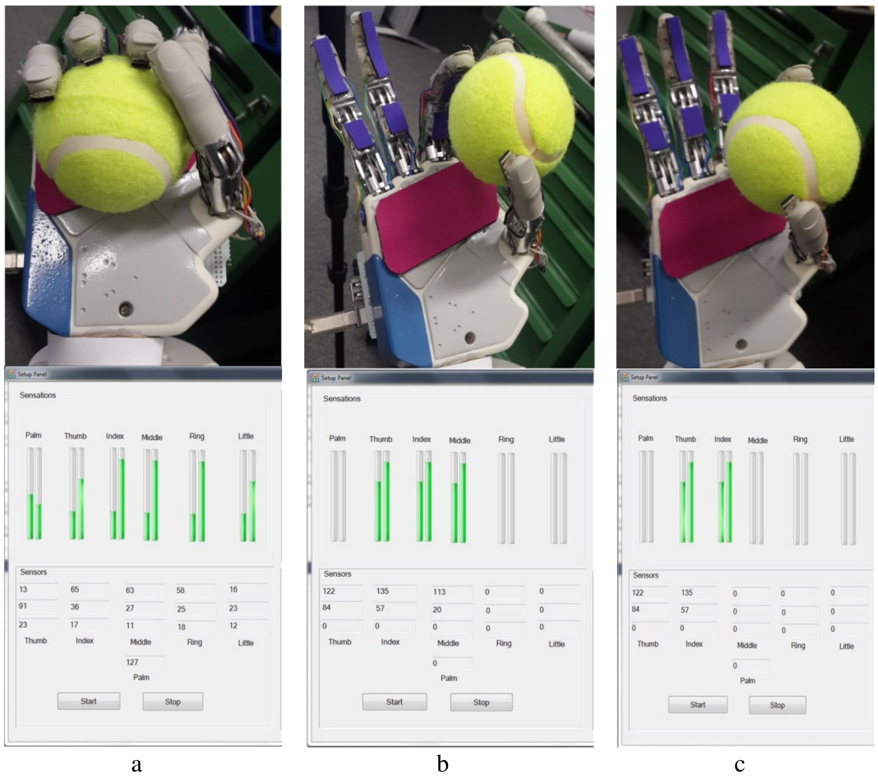


Fig. 8. Robotic hand gripping tennis ball with: (a) five fingers (b) three fingers (c) two fingers.

We conducted two experiments with five users to see if the electro-tactile feedback made it easier for a user to handle objects with the robotic hand. Prior to the commencement of each trial each user was asked to adjust the maximum level of intensity of the electro-tactile feedback signals to suit their preference. The first experiment involved picking up and putting down various objects with different grips. The second experiment involved gripping, holding and manipulating objects that have the similar size and shape but different weights.

For the first experiment, different objects, including a mobile phone, tennis ball and jam jar were placed on the table. The supervisor then demonstrated, with his own hand, how he wanted each object to be picked up and put down with the robotic hand.

Figure 8 shows examples of a user grasping a tennis ball with (a) five fingers, (b) three fingers and (c) two fingers. The green vertical bars on the user interface show the intensity and frequency of the electro-tactile feedback from the palm, thumb, pointer, middle, ring and little fingers respectively.

After 20 minutes picking up and putting down objects with the robotic hand, both with electro-tactile feedback turned on and off, each user was asked to comment on any effect the electro-tactile feedback had on performing these tasks. All users reported that the electro-tactile feedback improved their ability to pick up, hold and put down objects. The general opinion was that the electro-tactile feedback made them more aware of the object being held by the robotic hand with less need to use their eyes to see what the robotic hand was doing.

For the second experiment, objects with similar size and different weights were placed on the table (e.g. metal and plastic pipes, full and empty bottles) and the users were asked to alternate between picking up lighter and heavier objects. The users were also asked to apply only sufficient force to prevent the objects from slipping from the robotic hand's fingers and to manipulate the objects around within the robotic hand by moving the robotic hand's fingers.

We found, without electro-tactile feedback, most users frequently dropped the heaver objects and often applied more force than necessary to pick and manipulate the lighter objects. When the electro-tactile feedback was turned on, all users reported that they were able to quickly learn how much force to apply to pick up and manipulate objects without slippage. For example, figure 9 (a) and (b) shows a golf ball and a lighter plastic ball being manipulated between the thumb and pointer fingers and the different forces applied by the fingers. Similarly, figure 9 (b) and (c) shows a heavy metal pipe and a lighter plastic pipe being held by the robotic hand and the appropriate finger forces applied to maintain grip of these objects.

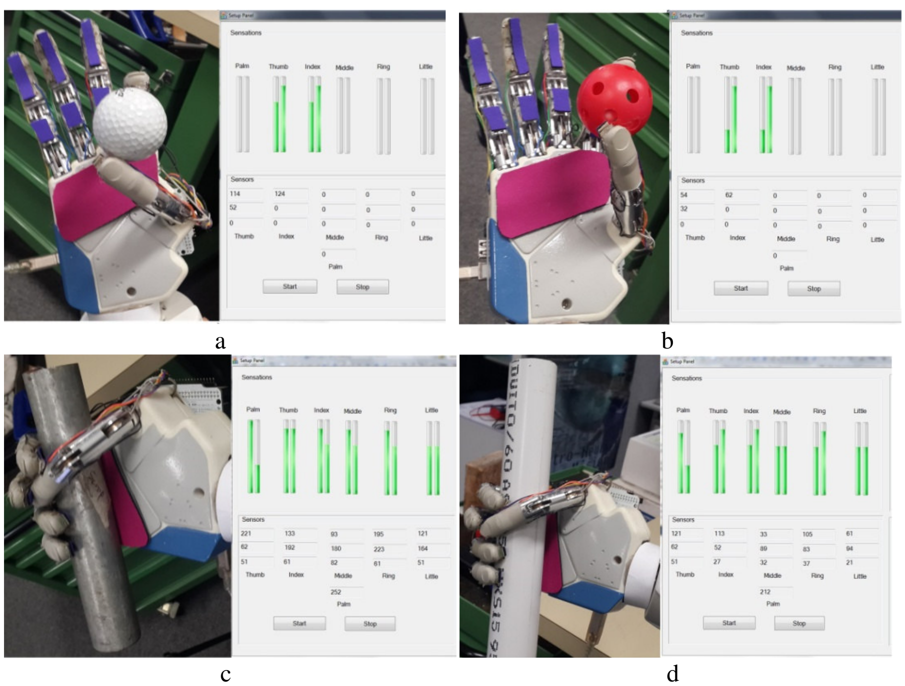


Fig.9. Robotic hand gripping: (a) a golf ball (b) a plastic ball (c) a steel pipe (d) a PVC pipe.

5 Conclusion

The development of a prosthetic hand capable of the same tactile sensations as a natural hand remains a major challenge facing prosthetic technologies. In this paper we present some preliminary results of our prototype electro-tactile feedback system for robotic and prosthetic hands. Our proposed electro-tactile feedback system is comprised of force sensors that can be placed almost anywhere on a prosthetic hand and TENS electrodes that can be placed on the user's arm or elsewhere. Our system has benefits in that it is inexpensive, multi-channel and can be fitted to existing robotic or prosthetic hands with relative ease. Although more extensive experimentation is needed to fully evaluate our system, our preliminary experimental results show that this form of tactile feedback can assist a user of an anthropomorphic robotic hand to become more aware of objects held and manipulated with the robotic hand. For future work we intent to conduct further experiments to see if this form of sensory feedback can enable the user to become more spatially aware of the robotic hand and its interactions with objects. We also intend testing our system on amputees with prosthetic limbs.

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