A Low-Cost, Open-Source, Compliant Hand for Enabling Sensorimotor Control for People with Transradial Amputations

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Abstract— **In this paper, we describe the design and implementation of a low-cost, open-source prosthetic hand that enables both motor control and sensory feedback for people with transradial amputations. We integrate electromyographic pattern recognition for motor control along with contact reflexes and sensory substitution to provide feedback to the user. Compliant joints allow for robustness to impacts. The entire hand can be built for around $550. This low cost makes research and development of sensorimotor prosthetic hands more accessible to researchers worldwide, while also being affordable for people with amputations in developing nations. We evaluate the sensorimotor capabilites of our hand with a subject with a transradial amputation. We show that using contact reflexes and sensory substitution, when compared to standard myoelectric prostheses that lack these features, improves grasping of delicate objects like an eggshell and a cup of water both with and without visual feedback. Our hand is easily integrated into standard sockets, facilitating long-term testing of sensorimotor capabilities.**

I. INTRODUCTION

The vast majority of open source hands focus only on mechanical design of the hands rather than the complete integration of motor control and sensory feedback systems [1]. Many of these hands involve hardware that require external power sources, housing, or custom sockets that are not practical for widespread usage. Much of this stems from the lack of development along side clinicans who design sockets to be used with commercial myoelectric systems. In this paper, we describe the design and implementation of a low-cost, open-source hand that can easily be integrated in to standard sockets made by clinicians. Furthermore, our hand integrates both motor control through electromyographic (EMG) pattern recognition and sensory feedback through contact reflexes and electrotactile stimulation.

The low-cost is especially important given that 80% of people with amputations are in developing nations, while less than 3% of them have access to affordable rehabilitative care [2], [3]. Additionally, the high cost of state-of-the-art myoelectric devices hinders researchers in evaluating effectiveness of new motor control and sensory feedback strategies. The prosthetic hand we present in this paper (Fig. 1) can be used for evaluating sensorimotor control and can be built for around $550. Furthermore, since this hand can be readily integrated into standard sockets, it facilitates long-term studies regarding motor control and sensory feedback in upper limb prostheses.

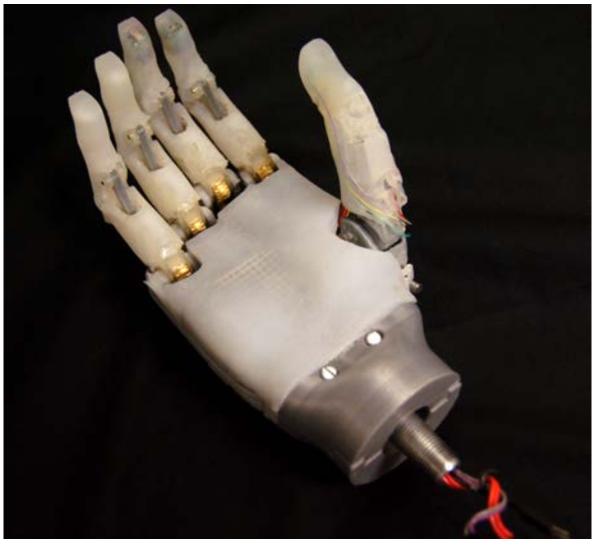

Fig. 1. The open-source prosthetic hand with EMG pattern recognition, contact reflexes, and sensory substitution capabilities. All files, designs, materials, and source code can be found on our website[1].

The paper is organized as follows—in Section II, we discuss the design of the hand, and the components used to enable EMG pattern recognition, contact reflexes through pressure sensors in the fingers, and sensory substitution. We also describe a set of experiments we performed on a subject with a transradial amputation to evaluate the performance of the contact reflexes and sensory substitution when using pattern recognition to grasp objects such as an eggshell or a cup of water. We compare these results to those from a standard OttoBock myoelectric prosthesis. In Section III, we describe and discuss the results of these experiments and their implications for further studies, followed by our conclusion in Section IV.

II. METHODS

A block diagram of the hardware is given in Fig. 2. The hardware was compartmentalized into three subsystems: 1) the socket, 2) the hand, and 3) the sensory substitution

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[1] http://bretl.csl.illinois.edu/prosthetics

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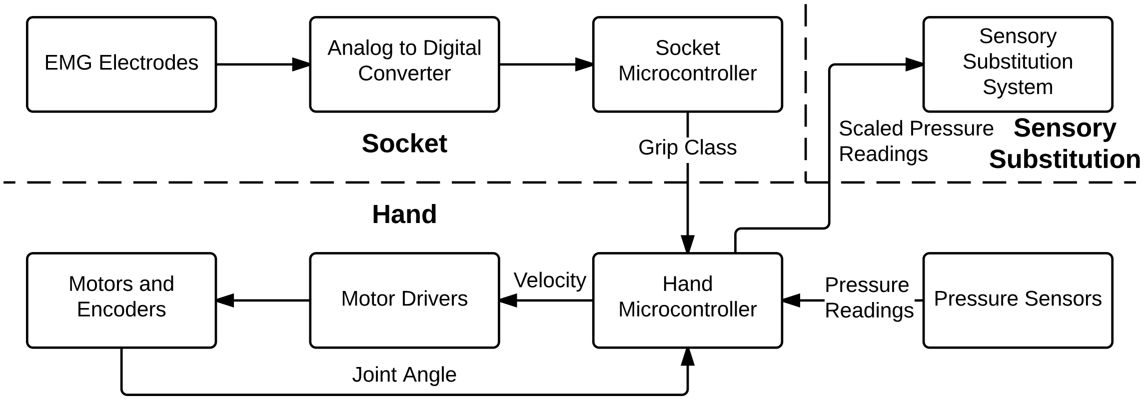


Fig. 2. Hardware Block Diagram

system. The socket collects and filters electromyography (EMG) data from the residual limb of the user, and runs the pattern recognition classifier used to associate EMG signals with one of five different grasping classes (rest, open, power, three-jaw chuck, fine pinch). The hand requests the classified grasp from the socket, and actuates up to six motors to perform the grasp. The six motors control flexion/extension in all five digits, as well as thumb opposition. In addition, the hand receives pressure readings from the three pairs of pressure sensors located in the fingertips of the thumb, middle, and index fingers. The sensory substitution system receives information from the hand about the pressure applied to the fingertips, and can give the user appropriate feedback regarding contact forces at the fingertips. In this paper, we used an electrotactile stimulation system to provide feedback to the user about contact forces.

A. Mechanical Design

Materials and costs required for building the hardware are listed on Table I. Compared to our previous work [1], the entire hand has been mechanically redesigned to be smaller, more robust through the use of compliant materials, and energy efficient through the use of non-backdrivable worm gears. The dimensions of the hand are at 50th percentile female anthropometry. Both PLA and ABS were used for 3D printing molds for silicone casting along with all structural components. Brass sprocket and worm gears were used for proximal joints due to their exposure to large loads and impacts. The fingers and palm are cast out of silicone to achieve compliance in the finger joints, providing human-skin like texture to the prosthesis. The compliant joints were developed by building a composite structure made of silicone (Dragon Skin 20, Smooth-On, Macungie, PA) and 3D-printed flexible material (SemiFlex, NinjaTek, Mannheim, PA). By using a flexible bone inside of a silicone outer structure, compliance in the distal and proximal joints was achieved. The joint compliance allows shock absorption from either flexion or extension directions. Non-backdrivable worm gears decrease power consumption when gripping objects with constant high torque. Although the worm gear set and motors are susceptible to environmental shock, the compliant joints prevent damage to the gears.

TABLE I

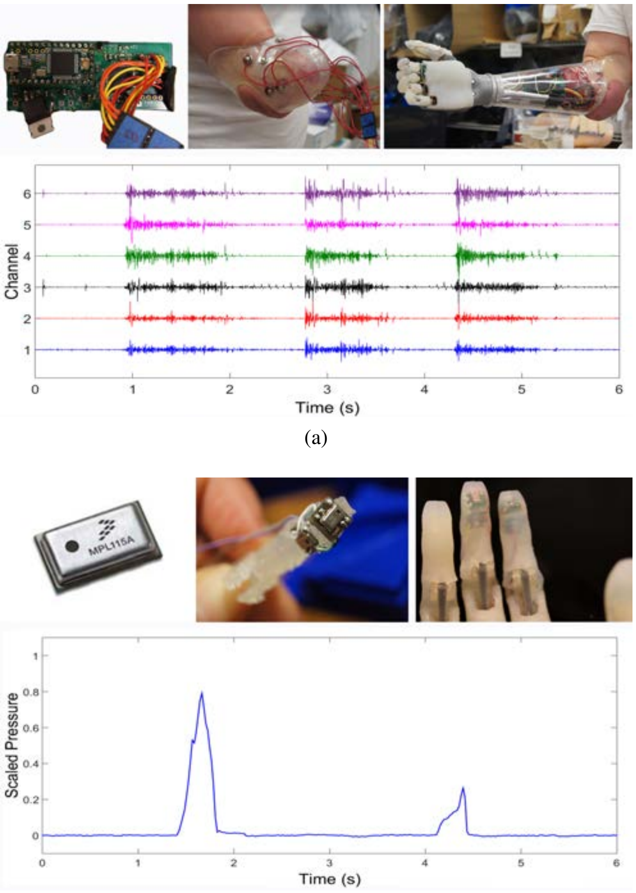
Cost of materials for building a single hand. Sources and prices for individual items can be found on our website[1].

Items	Cost
Microcontrollers	\$39.60
Integrated Circuits	\$89.59
Printed Circuit Boards	\$12.58
Electronic Passives	\$11.13
Electrical Power	\$63.35
Motors	\$128.55
Mechanical Components	\$126.28
3D Printing Materials	\$81.98
Total	\$553.06

B. Motor Control and Sensory Feedback

1) EMG & Pattern Recognition: EMG was used to control actuation in the hand (Fig. 3a). To save costs in electrodes, up to eight pairs of nickel-plated copper rivets can be used to record EMG signals from the residual limb of a person with an amputation, with an extra rivet being used as a ground electrode. Each rivet costs \$0.23 and can be easily integrated into a socket, while standard stainless steel dome electrodes typically cost around \$40 per electrode. These eight EMG channels and ground were connected to a custom board we fabricated using the TI ADS1298 (Texas Instruments, Dallas, TX) 24-bit analog-to-digital converter. The EMG signals were digitally filtered with a bandpass filter with cutoffs of 30Hz to 450Hz, and convolved with a notch filter at 60Hz. All signal processing was performed on a Teensy 3.1 microcontroller (PJRC, Sherwood, OR) in the socket.

We implemented Linear Discriminant Analysis (LDA) with proportional velocity control on the socket microcontroller as our pattern recognition algorithm [4]. In this paradigm, users undergo a 2-minute training period where they are asked to hold each of the five grasping classes for 25 seconds. LDA is then used to classify the user's desired grip every 75ms using a sliding window of the past 200ms of EMG signals. Proportional velocity control is implemented using the mean absolute value of the most active EMG channels for the desired grasp, as described by Scheme, et al. [4]. A Teensy 3.1 microcontroller in the hand uses the classified grasp and proportional velocity to control the



(a)

(b)

Fig. 3. (a) EMG board based on the ADS1298 chip on the top left. Nickel-plated copper rivets used in the socket as electrodes in the top middle, followed by all the electronics fitted into the hand/socket on the top right. Six channels of EMG are displayed in the plot below the images, corresponding to 3 hand open movements. (b) The MPL115A2 barometric pressure sensor in the top left image is embedded into a bone structure of a finger in the top middle image. The top right image shows the final finger with the pressure sensors embedded inside. Below the images is a plot of the pressure reading from a single sensor showing a strong pinch followed by a weak pinch.

velocity of the motors used to achieve the desired grasp.

2) Pressure Sensing & Contact Reflexes: The hand microcontroller polls three pairs of MPL115A2 barometric pressure sensors (Freescale, Austin, TX) located in the finger tip and finger pad of the thumb, index, and middle distal phalanges (Fig. 3b). Using the low-cost method described by Tenzer, et al. [5], we cast the sensors in silicone (Dragon Skin 20, Smooth-On, Macungie, PA) to turn them into highly sensitive touch sensors when depressing the silicone. The pressure readings from each sensor are scaled to a value between 0 and 1, and we detect contact when the pressure value exceeds a threshold of 0.2. If contact is detected in any of the six pressure sensors, a contact reflex takes place in which the speed of the hand is reduced to 30% of its current speed in order to provide the user with finer control in manipulating the contacted object without damaging it [6].

3) Sensory Substitution: In addition to providing contact reflexes, information from the pressure sensors can be delivered to the user via sensory substitution. In particular, we use electrotactile stimulation to provide this feedback, though any sensory substitution system, such as vibrotactile stimulation or skin stretch, can be used. Previous studies have shown that electrotactile stimulation can be effective in delivering information about contact to a user [7], [8]. The hand microcontroller communicates with a Teensy 3.1 microcontroller connected to a Biopac linear isolated stimulator (STMISOLA, Biopac, Goleta, CA). When contact is detected from any of the pressure sensors a 50Hz, 200μs constant current biphasic square pulse is delivered to the user at a predetermined current amplitude perceived to be a strong and comfortable sensation. Eventually, this system will be enhanced by adding more stimulation channels corresponding to each of the three digits with pressure sensors, miniaturized to a form factor that can fit within the socket.

C. Experiments with Subject with Transradial Amputation

In order to evaluate the effectiveness of our motor control and sensory feedback systems, we performed two experiments with a 39-year-old male with a right traumatic transradial amputation. The two experiments performed involved 1) grasping an eggshell without cracking it, and 2) grasping a cup partially filled with water. The subject performed each experiment with his OttoBock two-channel myoelectric hand, as well as the new hand we developed. To interface with our hand, a socket housing six EMG electrode pairs was fabricated to fit the subject's residual limb. Each experiment was done under visual feedback and no visual feedback conditions. Visual feedback was removed with the use of a blindfold. In the eggshell grasping task, the subject attempted to grasp a hollow egg held in his unimpaired left hand with his prosthesis ten times. The number of times the eggshell cracked upon grasping was recorded. The goal was to crack as few eggshells as possible out of the ten trials. In the water cup grasping task, the subject was asked to grasp a 266mL cup filled with 120mL of water. Upon grasping the cup, the volume of water displaced was measured by marking on the cup the new height to which the water rose. The goal was to displace as little water as possible when grasping the cup.

III. RESULTS & DISCUSSION

The results of the eggshell grasping and water cup grasping tasks are shown in Table II. Representative grasps from both experiments are shown in Fig. 4.

TABLE II

RESULTS FOR EGGSHELL GRASPING AND WATER CUP GRASPING TASKS.

	Visual Feedback	No Visual Feedback
Number of Eggshells Cracked (Original Myoelectric)	6/10	8/10
Number of Eggshells Cracked (New Hand)	0/10	0/10
Volumetric Displacement (Original Myoelectric)	19mL	73mL
Volumetric Displacement (New Hand)	12mL	19mL

When using his original myoelectric prosthesis, the subject cracked six eggs and eight eggs when visual feedback was


(a) (b)

Fig. 4. Experiments with (a) the subject's original myoelectric prosthesis showing him crushing the egg and cup. However, when using the new hand as shown in (b), he successfully grasps the egg without cracking it and grips the cup with minimal water displacement.

available and then removed, respectively. However, when using the new hand, the addition of contact reflexes helped to stop grasp closure upon contact with the egg, and no eggs were cracked in both visual and no visual feedback conditions. The addition of electrotactile stimulation feedback helped the subject during no visual feedback conditions, allowing him to know when he was making contact with the egg. Furthermore, in qualitative observations, the subject was easily able to control his prosthesis to pinch, three-jaw chuck, or power grasp the eggshell using pattern recognition when using the new hand.

In the water cup grasping experiments, the subject displaced 19mL and 73mL of water with visual and no visual feedback, respectively. When using the new hand, he only displaced 12mL and 19mL under visual and no visual feedback conditions, respectively. The addition of contact reflexes aided in decreasing the amount of volumetric displacement of water. The addition of electrotactile stimulation again helped when there was no visual feedback. In fact, when using his original myoelectric prosthesis, the subject experienced difficulty in knowing when he was grasping the cup of water when no visual feedback was present, resulting in him prematurely releasing his grip on the cup before lifting it. In this case, if stimulation feedback was present, he would be aware that he had released his grip before lifting the cup.

While previous studies [6] have suggested that stimulation feedback alone may not improve the user's reaction time to stop grasping once contact is made with an object, the advantage of stimulation feedback is evident when visual feedback is not available. Furthermore, when coupled with contact reflexes, another advantage of stimulation feedback is the improvement of the embodiment of the prosthesis [9]. This effect may be further enhanced when using multiple stimulation channels corresponding to each pressure sensor in the fingertips. To truly test the effect of embodiment, however, longitudinal studies need to be performed. For this reason, we have fully integrated all components into the socket and hand, excluding the sensory substitution system, which we plan to incorporate into the socket in future work.

IV. CONCLUSION

In this paper we described the design and implementation of a prosthetic hand that enables sensorimotor control for people with transradial amputations. Specifically, this hand integrates EMG pattern recognition with contact reflexes and sensory substitution, that can all be integrated with standard sockets to facilitate long-term testing. This hand can be built for around $550 and we have open-sourced all of the designs and materials so it can be built by those in the research community and in developing nations. We showed that the use of contact reflexes and sensory substitution improves the grasping of delicate objects like eggshells and a cup of water, when compared to standard myoelectric prostheses. Video of the hand in action, as well as all files, designs, materials, and source code can be found on our website[1].

V. ACKNOWLEDGEMENTS

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