Evaluation of Multi-Modal Tactile Feedback in Prosthetic Limbs

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ABSTRACT

While substantial research efforts have been put forth to advance the mechatronics and control of prosthetic hands, little attention has been paid to restoring the sensory functions of tactile feedback to amputees. It is known that the human hand when unable to feel through either disease or induced anesthesia becomes incapable of performing a number of essential dexterous tasks. Therefore, it is proposed that prosthetic hands without these capabilities will be no better. Tactile sensing in the human hand can be used for both autonomous reflexes and conscious perception. In a previous study we had explored using tactile sensing for autonomous reflexes to enable fragile object grasping [1], in this study we evaluate the benefits and performance in conscious perception of multimodal tactile information. A prosthetic hand equipped with a BioTac sensor (capable of sensing force, vibration and temperature) and multi-modal tactors developed to play back this information on a subject's forearm were used to evaluate perception in tactile discrimination experiments. Results showed that this system able to effectively convey information to the prosthesis user to identify and discriminate objects of different weight, temperature, thermal properties, or surface texture when they were placed between the subject's prosthetic fingertips. While this system was effective at providing useful perceptual feedback, the subject indicated that the majority of the tactors were distracting and would be undesirable for day-to-day use.

Keywords: Prosthetics, tactile sensing, tactile feedback, tactors, conscious perception, force tactor, vibration tactor, thermal tactor.

Index Terms: H.1.2 [Information Systems Applications]: User/Machine Systems -- human information processing; H.5.2 [Information Interfaces and Presentation]: User Interfaces -- haptic I/O

1. INTRODUCTION

In the US alone there are more than 1.6 million people living with the loss of a limb with upper-limb loss accounting for 68.6% of trauma related amputations and 58.5% of congenital birth defects [2]. Despite many efforts to advance prosthetic hand technologies to produce lighter weight devices with more degrees of freedom or advanced neural interfaces, less progress has been made to restore tactile sensing in amputees, which plays an important role in both tactile perception and dexterous manipulation. Studies have shown that a lack of tactile sensation in the human hand severely impacts coordination, the ability to determine appropriate grip force, and manipulate objects [3]-[6].

Two approaches have been suggested to make use of tactile information in prosthetic devices: tactile feedback can be used to enable autonomous reflexes making prosthetic hand control more natural and intuitive [1], and tactile information can be provided directly to the user for conscious perception. To provide tactile information to prosthesis users, many groups have developed tactile displays to stimulate the residual skin and nerves of an amputee. These technologies have ranged from non-invasive approaches using vibrators [7] or air pressure [8] to more complex approaches providing spatially-mapped tactile displays of pressure, vibration, shear force, and temperature [9], [10] in subjects who have undergone targeted reinnervation surgery [11].

Studies exploring tactile feedback in prosthetics frequently rely on sensory substitution, typically using vibration [12] or electrocutaneous stimulation [13] to convey physically different stimuli such as force, and typically face associated problems with habituation [14]. This work seeks to evaluate the effectiveness of multi-modal tactile feedback in a prosthetic hand fitted with BioTac® tactile sensors (SynTouch, LLC) capable of detecting force, vibration, and temperature. Tactile displays that provide mode-to-mode feedback (i.e. force sensing to force display, etc.) were developed to allow the user to receive direct feedback from the BioTac sensor with the goal of creating more functional and intuitive tactile feedback. Studies were conducted to determine quantitatively whether or not the use of these types of tactile displays provides an effective means of conveying sensory information to a prosthesis user and if the development of these technologies for commercial devices would be sensible.

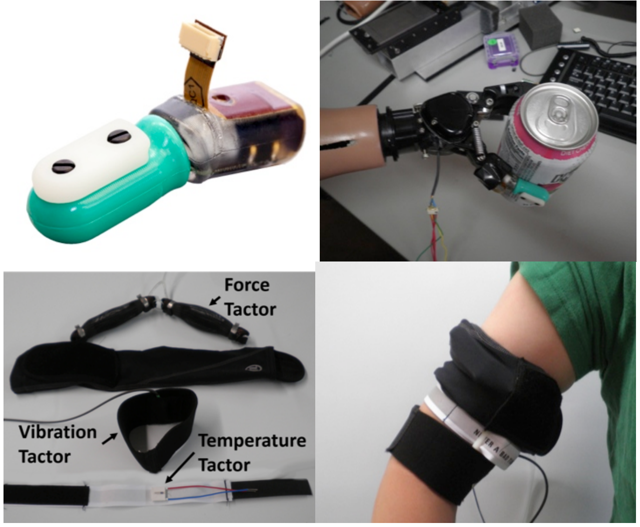

Figure 1: Top-Left: Multimodal BioTac tactile sensor, Top-Right: Prosthetic hand equipped with multimodal tactile sensors, Bottom-Left: Tactors, Bottom-Right: Tactors being worn.

2. MATERIALS AND METHODS

1.1 The BioTac

The BioTac (SynTouch) (Figure 1, Top Left) is a multimodal tactile sensor designed to mimic the sensory capabilities of the

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human finger. It consists of a rigid bone-like core covered with a silicone skin (Figure 2). The space between the skin and the core is inflated with a liquid giving the sensor biomimetic compliance comparable to primate fingertips [15]. The skin is easily replaceable and contains no electronics, making the sensor robust enough for everyday prosthetic use, yet easy to repair in the event of damage. The BioTac can simultaneously sense force [16], vibration [17], and temperature [18]. All data are digitized inside the device and transmitted via serial peripheral interface bus (SPI). Force estimates can be extracted either from a pressure sensor inside the fluid-filled chamber [19] or from an array of impedance-sensing electrodes [20]. In these experiments, contact forces were measured using the pressure sensor, which has been demonstrated to provide contact sensitivity that exceeds even human performance [17].

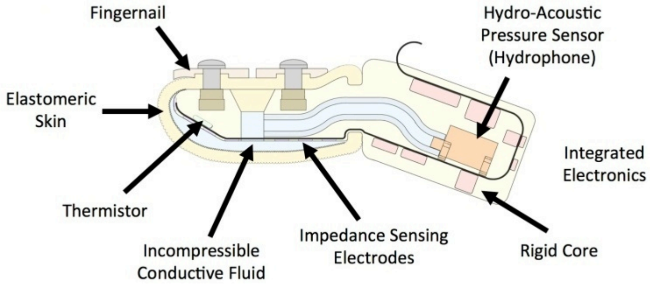

Figure 2: Conceptual Schematic of BioTac

For these studies a BioTac sensor was fitted on the index finger of a 1-DOF Myoelectric Prosthetic Hand (MC Hand, Motion Control) (Figure 1, top-right) using methods described in [1]. “Dummy” BioTacs (containing no electronics) were mounted on the middle finger and thumb to produce stable gripping points. The prosthetic hand was controlled using EMG signals being recorded from the subject’s socket and the controllers developed in [1]. Signals from the BioTac were collected in LabVIEW and processed to drive the tactors as discussed below.

1.2 Tactile Displays

Three tactile displays (Figure 1, bottom-left and bottom-right) were developed to convey force, temperature and vibration as measured from the BioTac to the upper-arm of an amputee. Signals to and from the tactors and supporting hardware were acquired and generated using a DAQ card (NI-USB 6218) and Analog Output card (NI-PCI-6722).

1.2.1 Force Display

To convey contact force measured in the BioTac, a series of pneumatic air muscles (30mm Air Muscle, Shadow Robot Company) were coupled in a loop to fit loosely around the upper arm of the subject. As the air pressure inside the air muscles increased, they stiffened and straightened out, producing a squeezing force on the subject’s arm. This display was driven by the fluid pressure reading from the BioTac (less the offset from the skin inflation) which was configured to drive a pneumatic PID controller (SPCU, Shadow Robot Company) that regulated the pressure inside the air muscles, providing a linear relationship between air-pressure inside the air muscles and command voltage. The full range of pressure measured in the BioTac over normal operation (approximately 10kPa) was linearly mapped between 0 and 200kPa of air-muscle pressure, which was found to produce a firm squeezing force, but not enough to restrict blood flow[1]. The time constant for the system was determined empirically to be 1.27s while inflating and 0.93s while deflating.

1.2.2 Thermal Display

To display temperature changes measured in the BioTac, a Peltier element (MCPF-031-10-25) was used to heat and cool the subject’s skin. AC Temperature signals from the BioTac were mapped between -0.75V and 3V to drive the element producing +/-3°C changes in skin temperature as verified by a thermistor between the Peltier element and the subject’s skin that continuously monitored temperature to ensure it did not go beyond these ranges to prevent injury. The time constant for the system was 8.485 s from 0 to 5 V (a decrease in temperature) and 12.38 s from 0 to -5 V (an increase in temperature).

1.2.3 Vibration Display

A standard cellular phone vibrator (16717, Toto Bay) was used to convey vibrations to the subject. The device produces larger vibrations as the voltage across its leads increases. To drive the device, AC Pressure signals from the BioTac were filtered with a sixth order Butterworth bandpass filter (250-300Hz) and then rectified and smoothed to produce a voltage in proportion to vibration intensity to control the vibrator.

1.3 Experiments

A single prosthesis user (male, age 20, unilateral amputee) with an upper-limb congenital deficiency, was fitted with the modified prosthetic hand and tactors for the experiments described below. In all trials the subjects vision and hearing were obstructed using a blindfold and headphones playing white noise to prevent this information from influencing the subject’s perception. Each of the experiments described below used a single tactor to evaluate each modality independently.

1.3.1 Force Perception

To test the subject’s ability to detect contact forces a small basket to hold weights was hung off the tip of a BioTac as the arm was rested on the edge of a table. Pressure was tared with the basket in place so that its weight did not drive the force display. The subject was told to indicate with his other hand’s thumb whenever he felt an increase or decrease in force from the force tactor. A weight was carefully placed into the basket and left for 5-10 seconds before removal. If the subject did not detect the weight he was notified by a tap on the upper arm when the basket was emptied to indicate the start of a new trial. 10, 20, 30, 50, 100, and 200g weights were used and presented to the subject in random order.

Weight differentiation was tested in a similar manner as above, however, two weights were presented for comparison. Each weight was placed in the basket for 5-10 seconds before removal. After each weight was presented the subject was tapped on the upper arm to indicate when the second weight was being placed and when the trial was over. After both weights were presented, the subject indicated by number of fingers whether the first or second weight felt heavier. Weights were presented in random order for the following pairs (values in grams): 200/100, 100/50, 120/100, 70/50, 110/100, and 105/100. In a variant of this test, the subject was also given the option of holding up three fingers to indicate that weights felt the same. For these studies the following weight pairs were used: 110/100, 105/100, 102/100, 100/100,

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[1] Air muscle pressure was related to, but not proportional to squeezing pressure, which was estimated to be approximately 30-40 times less.

110/110, and 102/102. All weights were presented to the subject in a random order both within and between trials.

1.3.2 Temperature Perception

The sense of touch permits for both the identification of a contacted object's temperature as well as the object's thermal properties. Since the human body is typically a few degrees warmer than the environment, certain objects (such as metals) tend to feel cooler because they conduct heat away from the body at a greater rate. The thermal sensing modality of the BioTac operates under the same principle taking advantage of built in heaters. Both basic temperature differentiation and material thermal property differentiation were tested.

To evaluate temperature discrimination, three cans of soda at different temperatures were used (room temperature: 25°C, cooled in a refrigerator: ~2°C, and heated in water bath: 60°C). The three cans were presented to the subject in a randomly ordered line. The subject was asked to grip each can in turn and then describe each can as hot, room temperature, or cold. For this experiment, the subject was allowed to use vision to grasp each of the visually identical cans with his prosthetic hand.

Material thermal property differentiation was tested by presenting pairs of materials with different thermal properties to the subject to grasp The subject gripped and held each object for 5-10 seconds before being offered the next. After a pair of objects had been presented, he indicated which object felt cooler. The materials presented (listed from high to low thermal conductivity) were: copper, stainless steel, plastic, and wood. Vision was obscured for this test and objects were supported on the table when presented so that the subject could not identify them by their weight. Materials were offered to the subject in a random order both among and between trials.

1.3.3 Vibration Perception

Humans perceive differences in texture based on vibrations that are sensed when their fingertips are slid over them [21]. To evaluate texture differentiation performance, materials of different roughness were rubbed against the BioTac finger on the prosthetic hand. Materials were offered in pairs and the subject indicated whether the first or second material felt rougher. The materials used (from roughest to smoothest) were foam, weave, cork, cardboard, and marble. Materials were offered to the subject in a random order both among and between trials.

3. RESULTS

1.4 Force Perception

Figure 3 shows the results of the weight recognition test. The subject consistently recognized both when the weight was placed in the basket and when it was taken out for the 100g and 200g weights. Performance was reduced in detecting the 50g weight, and the 10g and 20g weights were generally undetected.

Figure 4 and Table 1 display the results of the weight differentiation tests. When the weight differential was greater than 20g, the subject was able to identify which was heavier very accurately but below this threshold accuracy is lost. Table 1 displays the results for the three option weight differential experiments. The percentage of correct answers in this test was lower than the two option test for the same weight differentials as the subject often believed the weights were the same when they were not.

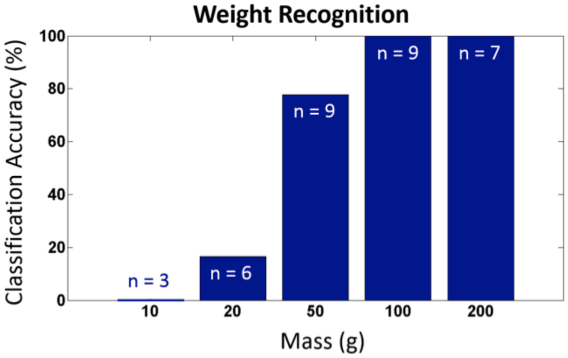

Figure 3: Weight recognition. The subject was able to reliably recognize weights greater than 20g. Below this threshold, correct recognition is severely diminished.

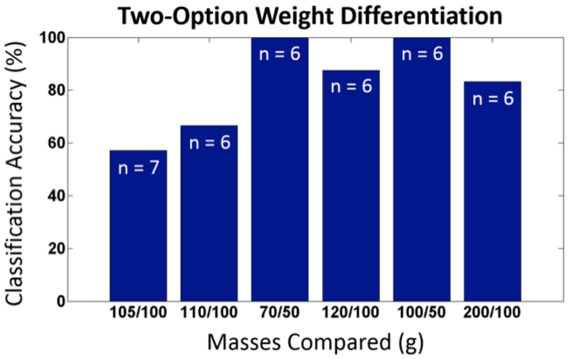

Figure 4: 2 option weight differentiation. For weight differentiation, accuracy is reduced when the difference is below 20 g.

			Incorrect	
		Correct	Reversed	Same
Masses Presented	100/110	3	1	1
	100/105	3	1	3
	100/102	2	1	1
	Repeated	2	1	--

Table 1. 3 option weight differentiation. The subject was not able to accurately differentiate between masses in this test and often indicated that he thought the masses were of the same weight when they were not.

1.5 Temperature

The subject was able to consistently differentiate between objects at different temperatures (Table 2) but was less accurate in differentiating between materials by thermal properties (Figure 5). Generally, the subject was able to quickly and easily identify which soda was hot, cold, and room temperature. Each trial took between 30 and 45 seconds. In the two cases where the subject indicated the hot soda as the room temperature soda and vice versa, it was the last run of the test and the hot soda was beginning to cool.

The subject was consistently able to differentiate between most materials based on thermal properties alone (Figure 5). He was also able to differentiate between objects with more dissimilar thermal properties, such as steel and wood, and was less accurate when attempting to differentiate between materials with more similar thermal properties, such as copper and stainless steel.

		Predicted Class		
		Hot	Room	Cold
Actual Class	Hot	9	2	--
	Room	2	9	--
	Cold	--	--	11

Table 2. Basic temperature differentiation. Temperature differentiation was consistently correct for all temperatures.

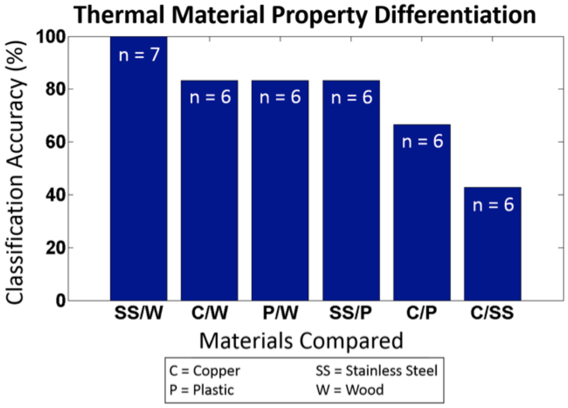

Figure 5: Differentiation of materials with various thermal properties was accurate for most materials.

1.6 Vibration

The subject was able to determine material roughness using the vibration display. All differentiations were accurate except foam/cork and cardboard/marble.

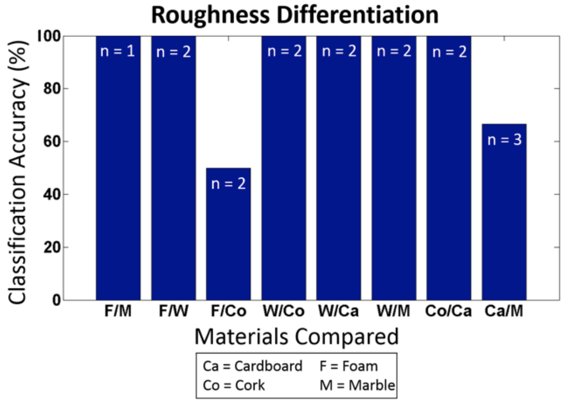

Figure 6: Vibration display was successfully used to differentiate objects by roughness in most cases.

4. DISCUSSION

The results of this study show that the tactile displays developed in combination with the BioTac sensor allowed the prosthetic hand operator to identify various tactile properties of objects. The subject was able to consistently recognize weights over 100g and differentiate weights that were more than 20% different in weight. At higher weights, discrimination became more challenging, indicating that the tactor was saturating or producing less information at the higher end. To correct for this a non-linear mapping could improve discrimination at higher forces if desired. The subject was also able to detect basic temperature differences and, surprisingly, even differences in thermal material properties with the thermal tactor. Preliminary testing of the vibration system also yielded promising results that exceeded expectations with such a simplified tactor. Additional performance may be seen using polyharmonic tactors.

Interestingly, while performance even exceeded the expectations of the subject, he reported that most of the tactors (particularly the vibration tactor) were rather distracting and would not be desirable for day-to-day use. As a unilateral amputee, he has the ability to perceive tactile properties (such as temperature and texture) with his opposing hand, which is indeed more effective. He did however find the force feedback to be useful and indicated it could be used to assess grasping quality and when contact is made.

5. CONCLUSIONS

There are many perceived advantages to be gained by feeding force, temperature, and vibration information back to a prosthesis user. It has been proposed that tactile feedback to the stump can help increase the feeling of ownership over a prosthesis permitting the prosthetic hand to feel less like a tool and more of an extension of the operator's body. Nonetheless, the functional utility of these devices may not outweigh the distraction they introduce or the costs to implement them in a commercially available product, particularly for unilateral amputees that are able to use their opposing hand for tactile perception.

The purpose of this study was to evaluate the performance of multimodal tactile displays when combined with multimodal tactors for prosthetic hand users, which was found to exceed expectations. However, with the exception of the vibration tactor, none of the tactors are suitable for a commercially available product, which would require light-weight devices with low-power consumption. While the force tactor was perceived to be of value to the subject, the requirements of an air-compressor and pneumatic control unit would be unsuitable for portable use. Based on subject feedback, mechanisms of delivering force information to the subject without vibrotactile displays should be explored further. The thermal tactor, while effective, would also be undesirable as the Peltier element consumes large amounts of current that would quickly drain the prosthesis' battery. While low-power vibration elements do exist (i.e. the cell phone vibrator used in this study), the subject reported it was the most "annoying" of the tactors. It is proposed that as vibration is a dynamic sense, meant mostly to detect isolated events a constant buzzing is both distracting and can lead to habitutation of the tactor. Further optimization could be done to improve tactor design and placement to improve performance, and meet requirements of a commercially available product, but it is unclear if the benefits would outweigh the associated costs in a product.

In previous studies [1], tactile feedback was used to create autonomous reflexes to grasp objects which was found to be highly desirable by the prosthetic operator (who was also a subject for these studies), but as addressed by the subject's feedback, using this information to drive tactile displays was found to be distracting. While each of the displays provided information to the subject to perform a task he could not previously complete, the distraction was perceived to interfere with other tasks of more interest to prosthesis users (such as grasping objects). Further studies would need to be conducted to evaluate the benefit of this information in comparison with the distraction they create before a practical set of tactile displays could become useful. Future research will focus on the development of the development of tactile reflexes which appears to be of higher value to amputees.

6. ACKNOWLEDGMENTS

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