A Tactile Display System for Hand Prostheses to Discriminate Pressure and Individual Finger Localization

Christian Antfolk1,* Christian Balkenius2 Göran Lundborg3
Birgitta Rosén3 Fredrik Sebelius1

1Department of Measurement Technology and Industrial Electrical Engineering, Lund University, SE-221 00 Lund, Sweden
2Department of Cognitive Science, Lund University, SE-222 22 Lund, Sweden
3Department of Hand Surgery, Skåne University Hospital, SE-205 02 Malmö, Sweden

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Abstract

No current commercially available myoelectrically controlled prosthetic hands provide conscious sensory feedback to the user. A system aiming at relocation of sensory input from a prosthetic hand equipped with force sensors to the forearm skin of amputees, a tactile display, has been developed and constructed. The system consists of five piezoresistive force sensors or, alternatively, a prosthetic hand equipped with force sensors, five digital servomotors with a lever and a circular plastic disk pushing on the skin, control electronics based on an MSP430 microcontroller and a test application implemented in LabVIEW running on a PC. The tactile display system is intended to be integrated into the socket of a hand prosthesis and used as a conscious sensory feedback system for hand amputees using a myoelectrically controlled hand prosthesis. The system will provide continuous force feedback from sensors in the fingertips of each prosthetic finger and will likely improve the users’ controllability and perception of the prosthetic hand. Here we report on tests made on “a five site” localization discrimination task and three pressure level discrimination tasks on the forearm of five healthy participants (non-amputees) using the LabView application to generate the stimulations. A mean five-finger discrimination accuracy of 86% and a mean three-level pressure discrimination accuracy of 93% were achieved, indicating the system to be a viable method of producing sensory feedback on the level of individual fingers.

Keywords: Sensory feedback, Tactile display, Hand prosthesis

1. Introduction

A tactile display is a device that mechanically stimulates a set of points on the skin to produce a specific sensory pattern. This sensory pattern can in principle represent different types of information, but here we are interested in how such a device, applied on the forearm in a future hand prosthesis, can represent pressure or force from an artificial hand and whether the stimulation produced by the tactile display on the forearm can give rise to a conscious perception of touch in a hand prosthesis and thus give a useful sensory feedback to the amputee during use of the prosthetic hand. Normally, in the intact hand, tactile feedback results from the stimulation and activation of mechanoreceptors in the skin responding to pressure (Merkels discs), vibration (Meissner and Pacini corpuscles) and stretching (Ruffinis corpuscles) and is important for the control of the hand. Perception of the shape of a novel object stems from signals from mechanoreceptors when working in an active exploratory procedure [1,2], i.e. merging sensory and motor information. Combining expectations from previous experiences [3] with contextual information and working memory forms representations of the shape of an object [4]. In addition, the mechanoreceptors of the hand and the sensory inflow are also necessary to produce the feeling that the hand is a part of the body. Lack of sensation from the hand can give rise to effects where the hand is no longer felt as a part of the body [5], much in the same way that a prosthesis is usually considered an extra weight or a tool rather than as a body part.

Since current myoelectric prostheses provide no conscious sensory feedback, controlling the force of a grasp is not easily learnt. Users often rely on visual feedback when controlling the grasp force. A myoelectric prosthetic hand with slip sensors that provide feedback to a intrinsic control system exists [6]. However, prostheses that do not have the ability to provide sensory feedback to the user have a higher risk of not being used [7-9]. Having force sensors in the fingertips of a prosthetic hand and subsequently providing sensory feedback using a tactile display could reduce the risk of users not wearing and using their prosthetic hands.

* Corresponding author: Christian Antfolk
Tel: +46-46-2229786; Fax: +46-46-2224527
E-mail: christian.antfolk@elnat.lth.se
Several tactile displays can be found in the literature which use different techniques for sensory feedback, including electrostatic and electromechanical systems as well as air jets, etc. [10,11]. Many of these tactile displays have focused on providing tactile feedback to the fingertips for use in, e.g., tele-surgery [12] or refreshable Braille displays [13] and for research in tactile perception [14]. In the area of prosthetic hand research, there have been some efforts to provide tactile feedback to the user by the means of vibrotactile stimulation, a tactile stimulation induced by a mechanical vibration of the skin. The CyberHand [15], the MANUS hand [16] and the Karlsruhe hand [17] have all been tested with vibrotactile systems. Another way to provide tactile feedback is to use electrotactile or electrocutaneous stimulation, i.e. tactile feedback induced by a current that passes through the skin. This was the approach taken by [9] and later in the Hokkaido hand [18]. Tests with providing both thermal and pressure or vibrotactile feedback were undertaken in [19] using a prosthetic hand. Yet another way to provide feedback is to use sensor substitution where another sense, in this case audition, was used to provide sensory feedback from the prosthesis [20]. None of these sensory feedback systems are available in prosthetic hands today.

The question we wanted to investigate in this study was whether it would be possible to use a tactile display to produce sensory feedback, and we tested this on a group of healthy non-amputee participants. The final aim is to apply the system in amputees using a hand prosthesis and toward this end, sensation will be recorded in the prosthetic hand using appropriate sensors and subsequently transduced onto the remaining forearm by means of servomotors. Each finger is represented by one actuator, i.e. in the present study five actuators were used. The basic idea of the system described and elaborated in this paper has been reported in [21] with a focus on the general concept of sensory feedback. Later the sensory feedback system was also tested on a single amputee in a case study [22] with promising outcome. In the present investigation, we tested the sensory system on a group of non-amputees using a novel training and evaluation setup, whereby the outcome was analyzed. Further technical improvement of the software regarding training methods and flexibility is reported. This work contributes to the understanding of the presented sensory feedback system, which is an ongoing development to provide useful and acceptable sensory feedback for hand prosthesis users.

2. Materials and methods

The sensory feedback system consists of three main components: (i) a matrix of actuators to be placed on the amputee’s stump providing the tactile feedback, (ii) sensors that can be mounted in a prosthetic hand or a prosthetic hand with embedded sensors and (iii) control electronics and software. A MSP430 microcontroller is the main part of the system and handles the communications and processing of all signals. A serial port (USART) on the microcontroller makes it possible to control the system from a PC in addition to the control based on piezoresistive sensors on the fingertips of a prosthetic hand.

Having a communication channel makes it possible to generate arbitrary stimulations by a computer and facilitates sensory feedback tests. The components are connected as described in the system block diagram in Fig. 1.

![Tactile Display system block diagram](image)

**Figure 1.** Tactile Display system block diagram. The Tactile Display system can be used with stand-alone FSR-sensors or using a prosthetic hand with integrated force sensors or controlled from a PC.

2.1 Actuators

The actuators used were digital RC-servos (Graupner DS281, Kirchheim/Teck, Germany). Traditional RC-servos were initially tested. However they were difficult to control in an accurate manner. Furthermore they did not produce enough torque to withstand the counter force of the skin. Digital RC-servos, on the other hand, have the required higher resolution and a faster control response. They also have increased holding power.

The servo shaft can rotate 0° and the rotational speed is 0.16 s/40°. The servos were controlled using a pulse width modulated (PWM) signal generated from a microcontroller. The position of the output shaft is proportional to the positive pulse-width, with a longer positive pulse-width producing a greater rotation of the servo shaft.

A 1-ms pulse width corresponds to a 0° rotation of the servo shaft, and a 2 ms pulse corresponds to a 90° degree rotation of the servo shaft (see Fig. 2). In our setup, the control signal was divided into steps of 100 μs. This means that the servo arm could be rotated in 9° increments. This could however easily be changed to smaller steps by reprogramming the microcontroller. Affixed to the servo shaft is a 15 mm long lever at the end of which is a circular plastic disk, with a 12-mm diameter, that is pressed against the skin. The circular plastic disk is fixed to the lever using a hinge mechanism to allow the circular plastic disk to always be parallel to the skin, see Fig. 3. Using a soft tube (Silopad Mesh Tube) with a matrix of holes for the actuators, different placement schemes are possible (see Fig. 3).

2.2 Sensors and signal conditioner

Piezoresistive sensors (FSR-149, IEE) can be used to control the tactile display system if a prosthetic hand without integrated sensors is used. Each sensor consists of two separated polymer membranes, one having a metal pattern and one consisting of a conductive polymer. When pressed, the two layers make a variable contact depending on the applied force.
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Figure 2. Pulse width modulated (PWM) signal.

Figure 3. Actuators (servomotors) placed on the forearm using a Silopad mesh tube.

An increase in the applied pressure causes more of the conductor material to make contact, which leads to a decrease in resistance that allows for a measurement of the applied force. The sensors have a diameter of ~7.5 mm, making it possible to integrate such sensors in a finger of a prosthetic hand. The resistance decreases from 10 kΩ to 1 kΩ as the force goes from 1 N to 100 N.

The signal conditioner consists of a low-power single supply voltage operational amplifier (TLV2404, Texas Instruments). It was coupled as an inverting amplifier and used to transform the resistance of the sensors to a measurable voltage. An RC single-pole low-pass filter with a cut-off frequency of 22.5 Hz was used as an anti-aliasing filter for the A/D converter of the microcontroller.

2.3 Microcontroller and driver

The microcontroller used was a MSP430F149 from Texas Instruments running at 8 MHz. The microcontroller has eight analogue inputs and a 12-bit A/D converter. Five of the analogue inputs can be used to read the piezoresistive sensor values. The A/D converter range of the microcontroller is 0-2.5 V and the A/D converter sampling frequency was set to 50 Hz for each channel. Five of the digital I/O’s of the microcontroller were used as digital outputs to produce the PWM-pulses that controlled the RC-servos. A CMOS non-inverting hex-buffer (CD4050, Texas Instruments) was used as a driver to prevent the servos from being sourced directly from the microcontroller.

A universal synchronous/asynchronous receive/transmit (USART) peripheral is available on the microcontroller and was used for communicating with a computer. A MM232R Mini USB-Serial UART development module (FTDI Chip, UK) was used to convert the signals from the microcontroller to USB-signals.

The speed of the serial interface is 230,400 bit/s at 8N1. This means that there will be 10 bits sent per byte. A total of 45 bytes is sent every 20 ms with the 12-bit (0-4095) sensor values coded in binary coded decimal notation, bytes to indicate which sensor and also a string of bytes to indicate whether the system is in sensor control or computer control mode.

2.4 User interface

A user application for a PC has been developed to enable a graphical user interface when testing the tactile display system (see Fig. 4). The PC software is more flexible, easier to use and

Figure 4. Tactile display system LabView application front end with control buttons and visual feedback representation.
it is faster to develop new test programs compared to re-programming the microcontroller. During tests, the PC software can be used to log the participant’s performance, for randomly selecting stimuli and to provide visual feedback to participants during training of the sensory system. It is also possible to set which hand is being stimulated (left or right) and how long the stimulation will last (in seconds). Ten different levels of displacement (rotation of the servo axis) for each actuator can be chosen by buttons on the graphical user interface.

The software was built using LabVIEW (National Instruments, Austin, Texas, US) to facilitate the testing and use of the sensory feedback system. Sensor values can be read to the LabVIEW program, making it easy to see how much pressure is applied. The servos can also be controlled using a protocol based on ASCII commands, making it possible to integrate the sensory feedback system in other systems. As the microcontroller also sends data in ASCII format, the hardware of the sensory feedback system can be used and debugged with a program like HyperTerminal.

2.5 Discrimination of pressure level and location tests

Five healthy participants of non-amputees, aged 27-32, including three men and two women, who had given informed consent, participated in the study. Two experiments were conducted on the participants, who had no prior training, to see how well they could discriminate five locations representing the five fingers of a hand and three levels of pressure on a single site of stimulation. The actuators were placed on the forearm of the participants in a U-shaped manner and with an actuator interdistance of ~4 cm (corresponding to the two-point discrimination threshold as identified in [23]) (see Fig. 3). In the tests, the previously mentioned LabView application was used to control the tactile display and hence elicit tactile stimulations.

During the tests, the participants sat in front of a computer screen with the arm in a relaxed position resting on a table. Sound-blocking headphones were worn at all times to prevent auditory stimuli from the sound of the servo motors. Prior to the actual test, the participants got acquainted with the system by looking at the computer screen to see which finger was stimulated in the location discrimination tests or at what level of pressure a single digit was stimulated in the pressure discrimination tests. Both in the acquaintance phase and the test phase, the stimulus was randomly selected and active for three seconds. During the test phase, the participants were blindfolded and had to guess the location of the applied stimuli, and after each guess were informed of the correct answer to avoid subsequent errors. Participants answers along with the stimuli properties were stored using the LabView program to enable later analysis. Comparisons between the answers from the participants and the actual stimulations were analysed to compute the discrimination accuracy. Fifty localization stimulations, randomly selected between the five sites and each with a duration of three seconds, were used in the localization discrimination tests and twenty-seven pressure level stimulations, randomly selected between low, medium and high pressure, were used in the pressure discrimination tests. The actuators were placed on the forearm of the participants according to Fig. 3.

3. Results

Each test session lasted approximately 45 minutes including donning the tactile display and setting up the hardware and the software. In Fig. 5, the accumulated accuracy of finger discrimination over successive stimulations can be seen. Participant 5 got the best score, with a final accuracy of 96%, and Participant 2 got the worst score, with a final accuracy of 76%. The average accuracy for all participants in the location discrimination tests was 86%, with a standard deviation of 8.4%. In Fig. 6, the accumulated accuracy of the pressure discrimination tests over successive stimulations can be seen; in this test, Participant 4 got a perfect score, and also here. Participant 2 got the worst score, with a final accuracy of 81%. The average accuracy for all participants in the pressure discrimination tests was 93%, with a standard deviation of 7.4%.

![Figure 5. Accuracy of finger discrimination over successive stimulations for the five participants. Y-axis denotes accumulated accuracy, and X-axis denotes increment in trials.](image)

![Figure 6. Accuracy of pressure level discrimination over successive stimulations for the five participants. Y-axis denotes accumulated accuracy, and X-axis denotes increment in trials.](image)
4. Discussion and conclusion

A sensory feedback system in the form of a tactile display was tested on five healthy non-amputee participants and showed a 93% average accuracy in the pressure discrimination tests and an 86% average accuracy in the localization discrimination tests using stimulations generated by a PC. Actuators in the form of digital RC-servos placed on the forearm skin relay sensory information to the user. The system is intended to be used in conjunction with a prosthetic hand with built-in force sensors or with piezoresistive sensors applied to a prosthetic hand, which are connected to the tactile display hardware and using a lever and a circular plastic disk pushing on the skin to provide tactile sensory feedback to the user. Some sensory feedback systems have been applied to prosthetic hands as noted in the introduction, however none of these systems provide multi-finger force feedback from the prosthetic hand. Instead they usually denote the total force of a grasp.

The number of sensors and hence the number of actuators were based on having one sensing element per finger of the human hand. The two-point discrimination threshold of the forearm is an order of magnitude less than the spatial resolution of the fingertips [23]. Thus, the actuator elements need to be placed with a quite high degree of separation on the forearm. This put restraints on how well the sensory input can be fed back to the users. One could never expect similar sensitivity as in a real hand, but the system has the potential to provide a basic sensory resolution.

In conclusion, the sensory feedback system may be a valuable assistance for the users of hand prostheses and provide a greater feeling of ownership of the prostheses. Future work should include tests on amputees and measuring the actual force acting upon the skin, which would then be fed back to the control system to enable a more precise control of the force feedback. A longer and/or repeated training session as well as repeated tests investigating long-term effects would also be interesting to investigate as the data presented shows an increasing learning curve for all participants. Further tests could also include definition of optimal localization sites for the actuators and investigation of whether the placement of the actuators can be changed over time, i.e. the re-learning potential in healthy participants as well as on amputees for feedback on the forearm.

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References
