On sensory feedback in hand prostheses

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On Sensory Feedback in Hand Prostheses

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Cover illustration
Illustration of the proposed sensory feedback system

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To whom it may concern

Abstract

Amputation of the hand implies the loss of the ability to grasp and the ability to "feel". The grasping function can be primitively restored using an active prosthesis. Multi-articulating electrically powered hands have recently made their way to the market and these hands provide enhanced grasping and gripping capabilities. However, these hands provide no direct and conscious sensory feedback to the user and there are ongoing research efforts in providing prosthetic hands with a sense of touch. There is no commercially available system for artificial limbs today that provides the user with conscious sensory feedback.

This thesis presents the development and experimental studies of a new concept for providing users of prosthetic hands with a conscious sensory feedback. Previous studies have mostly relied on "sensory substitution" methods where sensory feedback is delivered in a different modality or to a different location on the body. By using modality matched sensory feedback, e.g. if pressure is sensed at a prosthetic finger then pressure is fed back to the amputee, the amputee would not have to learn to interpret the feedback signal (e.g. pressure coded as vibrations). Furthermore, many amputees experience a phantom "hand map" in their residual limb and when specific areas of this map is stimulated, the stimuli is perceived as coming from specific fingers in the amputated hand. By utilizing the phantom "hand map", amputees can be provided with modality matched sensory feedback, delivered to the "correct" body location and activating the correct location in the somatosensory cortex.

In several studies, feedback actuators in the form of digital servomotors or air-mediated pressure bulbs were used to provide both non-amputees and amputees with sensory feedback. It was shown that amputees can learn to interpret sensory feedback on different locations and that the developed sensory feedback system would not interfere negatively with a myoelectric control system. Furthermore, it was shown that the use of modality matched feedback in a multi-site discrimination task yielded better results than modality mismatched sensory feedback. In conclusion, the studies indicate that this new concept for sensory feedback in hand prostheses can be useful in future artificial hands and enhance the sense of body ownership of the prosthesis.

List of papers

I **SmartHand Tactile Display : A new concept for providing sensory feedback in hand prostheses**
Antfolk C, Balkenius C, Rosen B, Lundborg G, Sebelius F.
J Plast Surg Hand Surg, 2010; 44: 50-53.

II **Design and technical construction of a tactile display for sensory feedback in a hand prosthesis system**
Antfolk C, Balkenius C, Rosen B, Lundborg G, Sebelius F.
Biomed Eng Online, 2010 ;9:50.

III **Referral of sensation to an advanced humanoid robotic hand prosthesis**
Rosén B, Ehrsson HH, Antfolk C, Cipriani C, Sebelius F, Lundborg G.
J Plast Surg Hand Surg, 2009; 43: 260-266.

IV **Transfer of tactile input from an artificial hand to the forearm: experiments in amputees and healthy volunteers**
Antfolk C, Cipriani C, Carrozza MC, Balkenius C, Björkman A, Lundborg G, Rosen B, Sebelius F.
manuscript

V **Sensory feedback from a prosthetic hand based on air-mediated pressure from the hand to the forearm skin**
Antfolk C, Björkman A, Frank S-O, Sebelius F, Lundborg G, Rosen B.
manuscript

VI **Artificial redirection of sensation from prosthetic fingers to the phantom finger mapping on transradial amputees': a comparison study between multi-site vibrotactile and mechanotactile perception**
Antfolk C*, D'Alonzo M*, Controzzi M, Lundborg G, Rosen B, Carrozza MC, Sebelius F, Cipriani C
* = equal contribution
manuscript

Author's contribution to the papers

Paper I: Performed the experiments and large part of the writing.

Paper II: Designed the hardware and software, performed the experiments and large part of the writing.

Paper III: Part of the experimental work and part of the writing.

Paper IV: Performed the experiments and large part of the writing.

Paper V: Part of the experimental work and part of the writing.

Paper VI: Performed the experiments and large part of the writing.

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1

Introduction

Losing a hand or a body part through amputation is a devastating event with the inevitable loss of both sensory and motor function resulting in a disability with enormous consequences for activities of daily living and quality of life [1]. A grasping function can be primitively restored using an active prosthetic hand. Multi-articulating electrically powered hands have recently made their way to the market and these hands will provide enhanced grasping and gripping capabilities. However, these hands provide no direct and conscious tactile sensory feedback to the user. Electrically powered hand prostheses are being used only to a limited extent by amputees with reported rejection rates of over 40% [2]. Myoelectrically controlled hand prostheses are difficult to control efficiently for an amputee and the main reason for this is that there is no direct sensory feedback from the prosthesis to the user [3]. Users often rely on visual feedback when controlling the prosthesis [4] and there are indications that users would like to give less visual attention to their device [5]. Furthermore, there are several survey studies indicating that one of the areas in need of improvement in upper limb prosthetics is the provision of sensory feedback to the user [2, 6, 7].

Artificial limb devices that feel and act just like real limbs would provide a more intuitive use. To achieve this goal, a prosthesis must have sensation, i.e. a tactile feedback. There exist no commercially available sensory feedback systems for artificial limbs today. The general process of providing tactile sensory feedback in a hand prosthesis is three-fold; 1) registration of tactile stimuli by an artificial receptor organ, i.e. sensors; 2) using actuators to transfer the tactile stimuli from the artificial receptors to intact skin; 3) interpretation by the central nervous system of the afferent signals. Various approaches to and designs of sensory feedback systems have been presented over the years (see a review in Chapter 5), but no proposed system has yet been convincingly proven usable and thus been made commercially available. The aim is to offer a prosthesis user a system providing a perception of touch as close as possible to physiologically natural perceived sensation. This implies a sensory feedback system that goes beyond an intrinsic loop between sensors and motors in a prosthesis which e.g. detects if an object is slipping and automatically adjusts the grip force accordingly without the awareness of the user. The technical solution should preferably be noninvasive, simple, durable, and not interfere negatively with the myoelectric or cosmetic functions of the prosthesis.

The general goal of this thesis is to develop a type of sensory feedback system that can mimic a naturally perceived sensation of touch. Amputees can experience phantom sensations and a "map" of the phantom hand can be presented on the residual limb [8, 9]. When specific areas of this map is stimulated, the stimuli is perceived as coming from specific fingers in the amputated hand [8]. These phantom phenomena are not homogeneous and each amputee presents with an unique combination of spontaneous or evoked sensations [10]. Functional magnetic resonance imaging (fMRI) results have shown that the organization in the somatosensory cortex of such phantom hands in amputees, following tactile stimulation of the hand map in the residual limb, corresponded topographically with that of a normal hand [11]. The skin area, the phantom hand map, serves as a potential target for tactile sensory feedback to amputees.

1.1 Aim

The aim of this thesis is to present and investigate a new concept for a sensory feedback system for hand prostheses. Tactile stimuli are picked up from the prosthesis and transposed to a "tactile display" on the forearm/residual limb and can thereby mimic a naturally perceived sensation of touch.

Key issues:

- Design and description of the technical solution of a sensory feedback system
- Investigate if and how well amputees and non-amputees can localise a stimuli and discriminate different pressure levels produced by the sensory feedback system
- Initial investigation of a feeling of body-ownership of a robotic hand
- Investigation of different types of sensory feedback

1.2 Outline

The outline of this thesis is as follows: Chapter 2 gives a brief overview of prosthetic hands currently available on the market and some of the state of the art in prosthetic hands research. Chapter 3 reviews how currently available prosthetic hands are controlled and some of the research endeavors in this area. Chapter 4 reviews amputations, their incidence and prevalence and gives a short introduction to the human sensory system and phantom sensations. Chapter 5 gives a brief review of sensors used in research prosthetic hands and what sensory feedback systems have been used in research. Chapter 6 gives a summary of the papers included in this thesis followed by Chapter 7 which gives an outlook to future endeavors.

2

Prosthetic Hands

Prosthetic hands, as a functional replacement for a lost hand or forearm, have been around for centuries. One of the first and most written about hands is the prosthetic hand of Gottfried von Berlichingen, a German imperial knight who lost his hand in the beginning of the the 16th century [12, 13]. His replacement hand was capable of holding objects from a sword to a feather pen and enabled him to continue his military activities. Cosmetic or passive hands has been around even longer, dating back thousands of years [14]. Replacement hands or prehensors comes in several types and shapes: hooks, hands, electrically powered, body-powered or passive hands all with different cosmetic coverings.

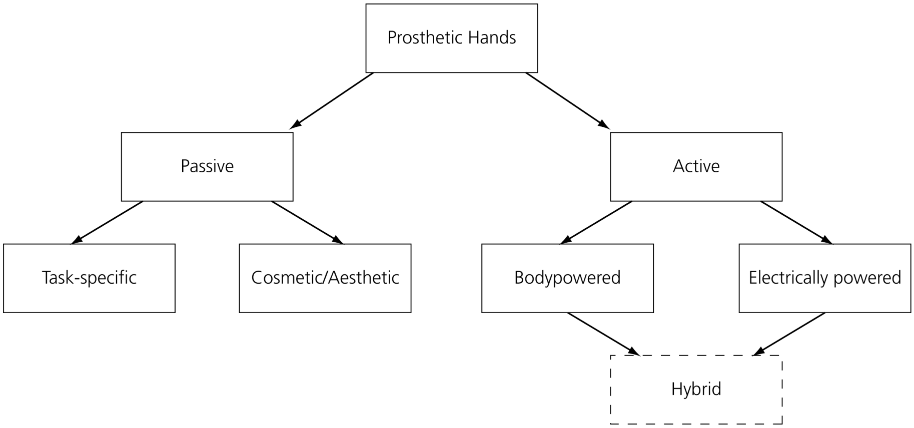

Figure 2.1: Classification of prosthetic hands

2.1 Passive prosthetic hands

From a functional point of view, hand prostheses can be classified into two main groups: passive and active prostheses (see Fig. 2.1). Passive devices are generally used in order to reestablish the cosmetic appearance of a missing limb (see Fig. 2.2) or they can be task-specific prostheses. A passive prosthesis cannot be actively controlled by the amputee (on some models fingers can be positioned) but it can mimic the appearance of a hand to great extent. Passive prosthetic hands are usually adopted by unilateral amputees who can use them as a support while performing a task with the other hand. Passive devices are simpler and lighter compared to active ones but they do not restore the grasping functionality to any higher extent. However, this type of prosthesis provides some limited functionality, such as pushing an object or aiding the non-injured hand during grasping or manipulation tasks. Task-specific prostheses are designed for a particular activity where other options would limit function or durability. These types of prostheses are commonly used for recreational activities such as swimming, golfing, hunting, playing ice hockey etc.

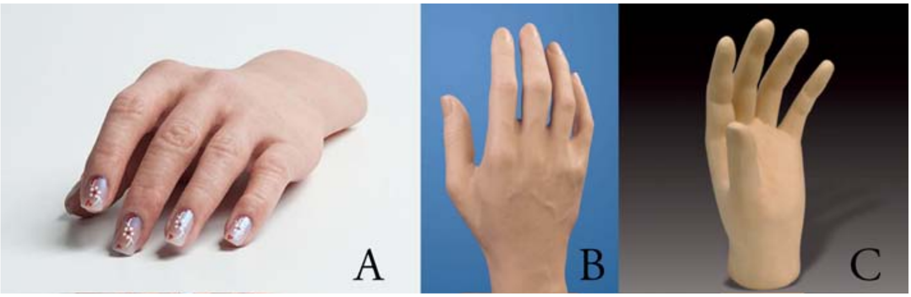

Figure 2.2: Examples of passive or cosmetic hands. A: Livingskin prosthesis (Image courtesy of Touchbionics [15]). B: Passive Prosthetic Hand (Image courtesy of Otto Bock [16]). C: Passive Cosmetic Hand (Image courtesy of RSLSteeper [17]).

2.2 Active prosthetic hands

An active prosthesis can be controlled by the amputee. Active prostheses can be further subcategorised into body powered and electrically powered prostheses. Body powered prosthetic hands (see Fig. 2.3) are controlled by harnessing the motions of other body parts and use cables to link movements of one part of the body to the prosthesis in order to control the opening or closing of the hand or hook. This is usually a movement of the shoulder or the chest, which is transferred via a Bowden cable (a single cable passing through a single housing) to activate the terminal device of the prosthesis. Body powered prostheses are usually of moderate cost and weight. They are quite durable and provide some sensory feedback of position through the harness [3].

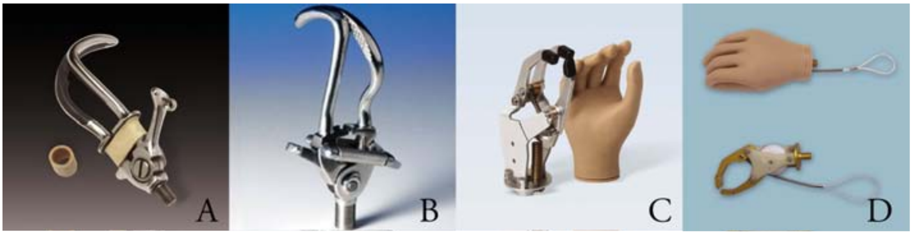

Figure 2.3: Examples of body powered/cable operated hooks and hands. A: Cable activated hook (Image courtesy of RSLSteeper [17]). B: Cable activated hook (Image courtesy of Otto Bock [16]). C: Cable activated hand (Image courtesy of RSLSteeper [17]). D: Cable activated hand (Image courtesy of Otto Bock [16]).

Electrically powered prostheses

Electrically powered prostheses (see Fig. 2.4) use small electric motors to provide movement and are usually controlled by using electromyographic (EMG) signals generated by the remaining muscles in the residual limb (more on this in the next chapter). Conventional electrically powered prostheses are simple grippers operating in an open/close fashion. They have one single motor to control the opening/closing of the grasp. Electrically powered prostheses do not provide the user with any direct sensory feedback. However, intrinsic feedback within the prosthesis controller, to prevent that an object slips, is available in certain models. Hybrid prostheses uses both electrically powered and body powered components in a single prosthesis. A hybrid prosthesis often use a body powered elbow and a myoelectrically controlled terminal device (hook or hand).

Figure 2.4: Electric hands and terminal devices (ETD). A: Motion Control hand (Image courtesy of MotionControl [18]). B: Centri hand (Image courtesy of Centri AB [19]). C: RSLSteeper hand (Image courtesy of RSLSteeper [17]). D: Otto Bock SensorHand (Image courtesy of Otto Bock [16]). E: Electrogreifer by Otto Bock (Image courtesy of Otto Bock [16]). F: Motion Control Electric Terminal Device (Image courtesy of MotionControl [18]).

Electrically powered dexterous prostheses

In the recent past, more dexterous prosthetic hands have emerged (see Fig. 2.5). These hands are commercially available and still quite expensive. They have several motors and control of individual fingers is theoretically possible (in some models). However, these prostheses use conventional EMG control systems (more on this in the next chapter) and their control possibilities are limited, sequential and to some degree unnatural. However, they do offer a wide variety of grasping capabilities and they are programmable.

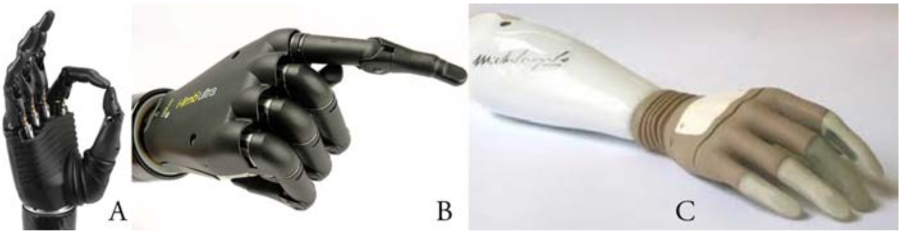

Figure 2.5: Modern electric hands. A: bebionic by RSLSteeper (Image courtesy of RSLSteeper [17]. B: i-Limb Ultra by touchbionics (Image courtesy of Touchbionics [15]). C: Michelangelo by Otto Bock (Image courtesy of Otto Bock [16]).

2.3 Prosthetic hands in research

Prosthetic hands research has been conducted for several decades (for a review on powered upper limb prostheses throughout history see [20]). Some of these prosthetic/robotic hands have reached a stage of maturity beyond that of research and may be commercially available in the near future (see Fig. 2.6). The Vincent hand by Vincent systems GmbH (see Fig. 2.6 A) [21] is equipped with six motors, one in each finger and one for thumb opposition. The fingers move in the metacarpophalangeal (MCP) joint, the distal interphalangeal (DIP) joint and are fixed in the proximal interphalangeal (PIP) joint. This hand build upon the research performed at Karlsruhe Institute of Technology (KIT) and the hydraulically actuated hands developed there such as the Ultralight hand [22] and the Fluidhands [23, 24]. These hydraulically actuated hands have flexible fluidic actuators in each joint of the fingers (MCP, DIP, PIP joints) and in the newest version a holding force of 65 N can be achieved.

As a part of the DARPA Revolutionizing Prosthetics 2009 Program two different hand prototypes were developed at Vanderbilt University (see Fig. 2.6 B). The Vanderbilt hand with extrinsic actuation [25] has five independent actuators that drive the fingers of the hand; one actuator for index finger flexion, one for middle finger flexion, one for thumb flexion, one for thumb opposition and one actuator that drives both the little and ring finger. The hand has 16 joints and fingertip forces of 20 N and a time to close of 400 ms. Another hand was developed by Vanderbilt University [26, 27] which has all the motors placed within the hand (i.e. intrinsic actuation). The hand has four motors: one motor for thumb opposition, one for thumb flexion, one for index finger flexion and one motor that drives the middle, ring and little finger.

The SmartHand transradial prosthesis [28, 29], was developed in the homonymous EU-project and it is based on the Cyberhand prototype [30]. The SmartHand is actuated by four motors; one motor for thumb opposition, one for thumb flexion, one for index finger flexion and one motor for the joint flexion of the middle, ring and little finger. It is equipped with a total of 40 sensors including 15 joint sensors, five tendon tension sensors, four tactile sensors, eight motor sensors and eight limit switches. A further development of the SmartHand is marketed by Prensilia as the IH 2 Azzurra (see Fig. 2.6 C).

A new hand system is under development at the University of New Brunswick [31, 32] and the aim is to produce a compact, life-like and affordable hand with a novel cosmetic glove and sensors. The hand uses three DC motors, with independent actuation of the index finger, linked actuation of middle, ring and little fingers, and a third motor driving the thumb. The MCP and PIP joints of the hand are linked and the DIP joint is fused.

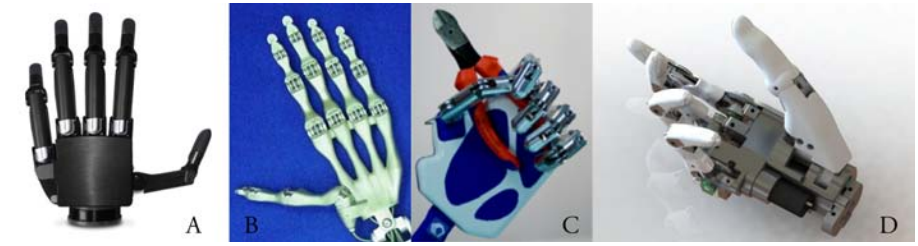

Figure 2.6: Examples of hands in research and development phase. A: Vincent Hand by Vincent Systems (Image courtesy of Vincent Systems [33]). B: Vanderbilt University hand (Reprinted from [25] © IEEE). C: IH2 Azzura hand by Prensilia (Image courtesy of Christian Cipriani (Scuola Superiore Sant'Anna). D: UNB Hand (Reprinted from [32] under Creative Commons).

In Sweden, the first generation SVEN hand [34, 35] and the second generation ES hand [36] were developed in the 1960-1980's. The SVEN hand had four motors, one driving the fingers, one driving the thumb, one for wrist flexion/extension and one for pronation/supination. In the SVEN hand the thumb could be locked in an outwardly rotated position and adaptive grasps were possible. In the ES-hand the thumb could be passively adjusted between a threepoint grip and a lateral grip [36] (cf. the i-Limb or bebionic hands).

The MANUS hand [37, 38] developed at CSIC in Spain has three motors. One DC motor actuating the index and middle finger, one DC actuating the thumb (for both opposition and flexion/extension) and one ultrasonic motor driving pronation/supination of the wrist. Hall effect sensor are used to measure both position and force of the thumb, index and middle fingers.

At the University of Southampton the Southampton-REMEDI hand [39] was developed and it is driven by six motors. Each finger is driven through a worm-wheel and the joints of the fingers are linked using a six bar configuration. Later this hand has been endowed with temperature, slip and force sensors [40, 41].

The TBM hand developed at the University of Toronto and the Bloorview MacMillan Center [42] has a finger design based on linkage bars (similar to the Southampton-Remedi hand). It uses only one motor to drive the flexion of all fingers and thumb (though a cylinder spring system) and rotation of the thumb is performed manually (similar to the bebionic and i-Limb hands).

Another hand prototype was developed as a part of the DARPA Revolutionizing Prosthetics 2009 Initiative termed the Intrinsic hand [43, 44]. It has 22 degrees of freedom and is driven by 18 motors. The index, ring and little finger are each driven by three motors, one motor for ab/adduction, one for driving the proximal phalange and one motor for driving the distal and medial phalange through a differential drive mechanism. The thumb is driven by four motors and the wrist is driven by three motors enabling wrist flexion/extension, radial/ulnar deviation and rotation.

3

Control of prosthetic hands

Prosthetic hands can be controlled in various ways. In this chapter some of the most common ways of controlling prosthetic hands and some of the proposed research methods are reviewed.

3.1 Conventional control strategies

A body powered cable-operated active prosthesis (hook or hand) can be either of a voluntary opening design (most commonly used) or a voluntary closing design. With a voluntary opening mechanism, the terminal device is closed at rest and conversely with a voluntary closing mechanism the terminal device is open at rest. The amputee uses the control-cable motion to open or close the terminal device against the resistive force of rubber bands (hook) or internal springs or cables (hand). The movement of the cable is often provided by moving the shoulder blades which pulls on a harness and consequently opens or closes the terminal device. The number of rubber bands or types and number of springs determines the amount of prehensile force that is generated.

Another form of "body powered" control is the so called Sauerbruch-Lebsche-Vanghetti cineplasty [45, 46]. In this technique a surgical fitting of a lever to a muscle in the residual limb is performed to facilitate the operation of an artificial hand or hook. The procedure involves a surgical isolation of a tunnel in the muscle of the chest or arm, covering it with skin, placing a lever through the tunnel and attaching the lever to a prosthetic device to be operated by the contraction of the muscle.

3.2 Myoelectric control strategies

Myoelectric control uses the electrical activity of a contracting muscle as a control signal. In a myoelectric prosthesis, the remaining muscles in the residual limb are used to provide control signals for powered components. Electrodes that record the myoelectric signals are placed over one or two muscle sites.

A one-site control system can be either two-state or three-state control (see Fig. 3.1). In the two-state control, if the myoelectric signal picked up at a single site exceeds a threshold the prosthesis opens and when the signal is below a threshold the prosthesis automatically closes. This is similar to a body powered voluntary opening prosthesis. In the three-state control, two thresholds are used (a "low" and a "high" threshold). If the signal is below the low threshold the prosthesis stops, if the signal is above the low threshold and below the high threshold, the prosthesis closes and if above the high threshold the prosthesis opens.

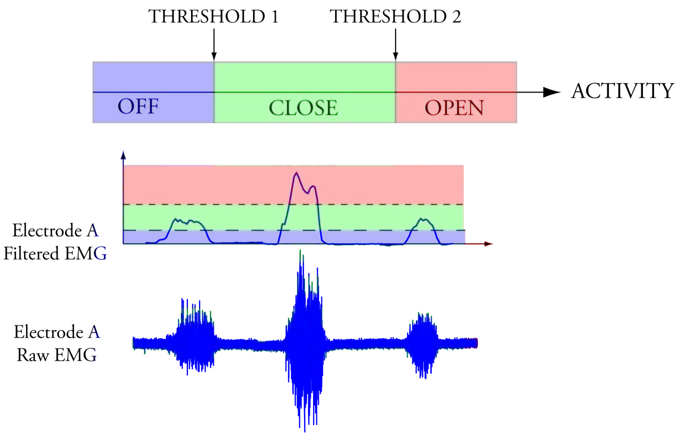

Figure 3.1: Example of one-site three-state control system

A widely used system is the one termed two-site, two-state control (see Fig. 3.2). Here, if electrodes over one site pick up a signal exceeding a configurable threshold, the hand opens. Conversely if electrodes over the second muscle site pick up a signal exceeding a threshold the hand closes. In the absence of a signal or if below threshold the hand stops. This system has the advantage of being quite "natural" if flexor muscles can be used to close the hand and extensor muscles to open it. This may however not always be the case and much training of the amputee is needed in order to produce stable and reproducible signals.

The previously described system have been on-off control systems, but the typical two-site, two-state control system also has a proportional speed control. That is, the magnitude of the filtered myoelectric signal controls the speed of the hand when it is closing or opening. If two powered components are used (e.g. a hand and wrist), both of them can be controlled using the two-site, two-state control. A co-contraction of the muscles (i.e. a signal exceeding the threshold on both sites) can be used to switch between which of the two components are controlled. A similar scheme is also often adopted in the control of multi-articulating prosthetic hands (such as the i-Limb or bebionic hand). Here, a multitude of grip patterns and gestures can be synthesized using the above mentioned scheme. Furthermore, in these hands, as the thumb is manually positioned (opposed or non-opposed), a signal can be derived from the position of the thumb and this signal will give further grasp patterns. An example configuration could be, with the thumb "opposed" two grasp/gesture patterns could be performed (pointing the index finger and a lateral grasp) and with the thumb in a "non-opposed" position similarly two other grasp patterns could be performed (a precision grip and a power grip). The disadvantage with this control method is that it is sequential and a number of actions needs to be performed to ensure that the controller is in the right state.

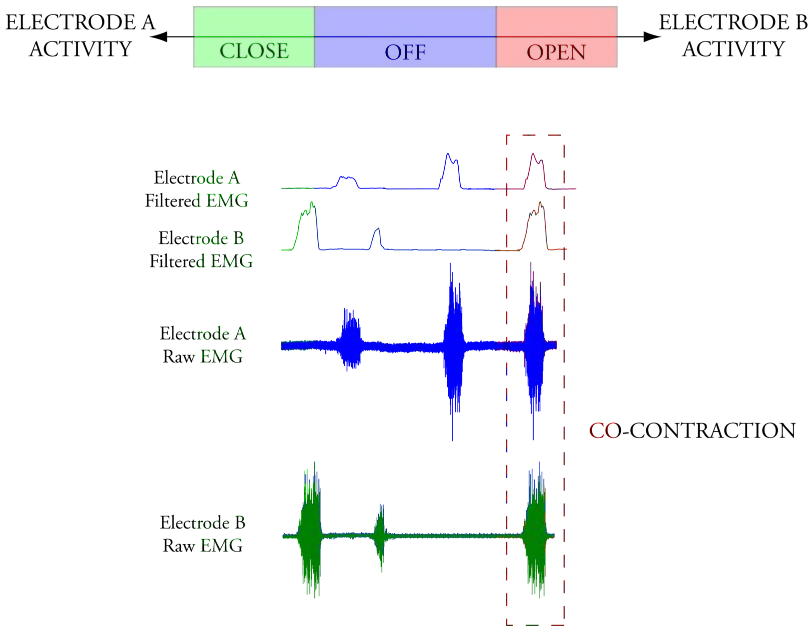

Figure 3.2: Example of two-site, two-state control system

The above mentioned control methods have been described based on a myoelectric signal. However, force sensing resistors (FSRs') could also be used in certain circumstances. With a rigid socket surrounding the residual limb a FSR could be used to detect pressure against the socket when a muscle is contracted. Furthermore, if the cable running from the harness in a body-powered prosthesis is connected to a linear transducer a control strategy similar to the one-site control system can be used to control electrical terminal devices using a body powered approach.

3.3 Multi-articulating pattern recognition control

As more multi-articulating hands emerge on the market such as the i-Limb and bebionic hands, capable of performing a multitude of grasps, the need for a more advanced control strategy than the ones previously mentioned is evident. Furthermore, controlling more than just the hand (e.g. the wrist or the elbow) also requires more advanced control strategies. The classical research approach to this problem is to use some sort of pattern recognition system.

Classifying surface EMG recorded on the residual limb of amputees into different movement types using different pattern recognition algorithms is often used in research in upper limb prosthetics (for recent reviews see [47–50]). Several different classifiers have been explored in the literature, however none of them have made it to the market for prosthetic hands. One of the earliest attempts at controlling prosthetic hands using the pattern recognition approach dates back to the end of the 1960's [51].

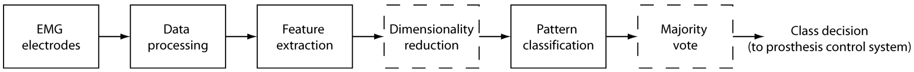

Figure 3.3: Pattern recognition control block diagram

Pattern recognition control relies in this context on having multiple inputs of myoelectric, or other, signals from which a number of features are extracted and these features make up the feature space from which classifications are made (see Fig. 3.3). Grasp primitives are commonly used to make up the classes.

EMG-signals are picked up on the residual limb usually using differential amplifiers with a high gain ($\sim$ 60 dB) and a high common mode rejection ratio (> 100 dB). The bandwidth of these amplifiers is typically in the range of tens to hundreds of hertz. The filtered and amplified signal is then sampled (typically in kilohertz) and further digital filtering is possible. Thereafter features are extracted using a windowing method (usually with overlapping windows). If a large number of features are extracted, a dimensionality reduction may be performed. After these processing steps, classification of the features is performed. To get an even higher classification accuracy of the system a majority vote approach can be considered, where the most occurring class in a number of past decisions is computed.

Pattern recognition control offers the possibility to perform a large amount of grasps with a prosthesis. However, there are obstacles that need to be overcome before pattern recognition can become a practically viable option for prosthesis control. One issue is that of limb position and limb loading, where using the arm in a variety of positions will cause a loading of the muscles inside of the prosthetic socket which will alter the EMG signal. Suggested ways of mitigating these effects include training with the arm in several positions or adding sensors to monitor the position of the arm and force sensors in the socket/hand interface [52–54]. Another issue is that of having proportional control (speed/force). Classifiers will usually only give information of the type of grasp or movement, but no information about the force. Schemes to overcome this issue includes the use of training sets where different amounts of force are produced for each grasp/movement [50], velocity estimates [55], intramuscular EMG [56] or mirrored bilateral training [57]. Finally, simultaneous control of several degrees of freedom, for example simultaneous control of both wrist and hand movements, needs to be developed. The use of parallel classifiers may be a way to accomplish this [58]. The use of one classifier per degree of motion in a prosthetic hand could possibly be a way of providing individual and simultaneous control. Another way of providing control signals for prosthesis control that has been suggested is termed Targeted Muscle Reinnervation (TMR) [59–61], where remaining arm nerves are transferred to residual chest or upper arm muscles that are no longer biomechanically functional due to the loss of the limb. Once reinnervated, these muscles serve as biological amplifiers of motor commands from the transferred arm nerves and provide physiologically appropriate EMG signals for control of the elbow, wrist, and hand. Other possibilities include the use of intramuscular EMG recording using needles, wires [56, 62] or implantable devices [63, 64]. Hargrove *et al.* [62] found no difference in classification accuracy between intramuscular and surface EMG using pattern recognition techniques. Using information directly from peripheral nerves of amputees to control a prosthesis has also been tested [65–69] (for recent reviews on this subject see Yoshida *et al.* [70] and Micera *et al.* [71]). Hochberg *et al.* [72] showed that signals from the motor cortex could be used to control a prosthetic hand. Velliste *et al.* [73] showed three-dimensional control of an arm and control of grasping in a feeding task with a monkey and Acharya *et al.* [74] showed that individual finger and wrist movements could be decoded using cortical signals. While these results based on cortical signals are promising for individuals with a spinal cord injury, their application to the control of prosthetic hands in amputees are debatable.

4

Amputation and sensation

An amputation may be the result of a traumatic injury, or it may be a planned surgical intervention in order to prevent the spread of e.g. a malignant disease or an infection in an extremity. A person might also be born without a limb (congenital limb deficiency). Kirkup [13] describes the nature of amputation as natural causes (e.g. congenital absence, diabetes or tumors), auto-amputation (trauma) or ritual, punitive, legal or Iatrogenic. Amputation of the upper limb can be at different anatomical levels (see Fig. 4.1). In the International Statistical Classification of Diseases and Related Health Problems 10th revision (ICD-10) amputations are classified as traumatic and at different levels (ICD S48, S58, S68, T11) or as congenital (Q71 and Q73).

Hand replantations or reattachments of traumatically severed limbs can be performed if a "clean amputation" has occurred and there is minimal damage to the residual and detached limb [13]. Romero-Zarate *et al.* [75] report a 82% success rate in replantation over three years. A study by Graham *et al.* [76] showed that replantation produces better functional results compared to amputation and a prosthesis. The transplantation of hands, where hands from deceased donors are transplanted to amputees, was performed for the first time in 1964 [77]. It is still fairly uncommon because of the need of immunosupressive therapy. In 2009, 44 hand transplants have been performed (20 patients had one hand transplanted and 12 patients had both) [77].

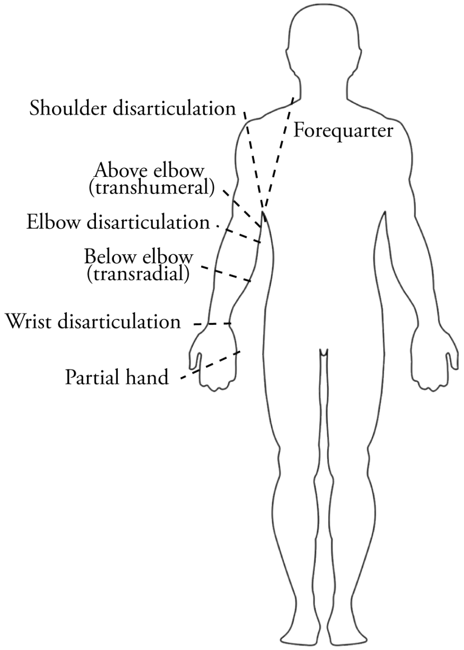

Figure 4.1: Upper limb amputation levels

4.1 Upper limb amputation incidence and prevalence

The incidence and prevalence rates of upper limb amputations are difficult to estimate mainly because estimates in the general population have been funded by diabetes research and focuses on dysvascular-disease-related (and primarily lower limb) amputations [78]. Ziegler-Graham *et al.* [79] estimated the prevalence in 2005 in the USA to 541,000 upper limb loss of which 41,000 were major limb losses and 500,000 minor limb losses (amputation of fingers or hand). This means roughly 13.6 major limb losses per 100,000 US citizens. Østlie *et al.* [80] estimated a population prevalence of 11.6 acquired major upper limb amputations per 100,000 adults in Norway. Upper limb amputations in the United Kingdom between 2005 and 2006 were 215 of which 126 were major amputations (through or proximal to the wrist). As a comparison there were 4574 lower limb amputations according to the amputee statistical database for the United Kingdom [81]. Amputations of the upper extremity are about 20 times less frequent than those of the lower extremity [82].

4.2 Human sensory system

The human sensory system is divided into the central nervous system (CNS), and the peripheral nervous system (PNS). The CNS is made up of the brain and the spinal cord and the PNS is made up of neural tissue outside of the CNS [83]. The human body is covered with different sensing elements or receptors that can detect a wide variety of stimuli. The somatic sensory system transmit information about four modalities: touch, proprioception, pain and temperature. These modalities share the same type of sensory neuron (dorsal root ganglion neuron) but have different receptor types. Temperature is mediated through thermal receptors, pain is mediated through nociceptors and touch and proprioception is mediated through mechanoreceptors. There are four main types of mechanoreceptors [84]: Meissner's corpuscles, Merkels' discs, Pacinian corpuscles and Ruffini endings. These receptors can be categorized based upon their individual properties. Meissner's corpuscles (also referred to as fast adapting type I, FA-I) are sensitive to skin deformation in the range of ~5-50 Hz and insensitive to static deformation. Merkels discs (also to as slowly adapting type I, SA-I) are sensitive to low-frequency dynamic and static deformations. Pacinian corpuscles (also referred to as Fast Adapting type II, FA-II) are sensitive to vibrations in the range of ~40-400Hz and insensitive to static force. Ruffini endings (also referred to as Slow Adapting type II, SA-II) are sensitive to static force.

4.3 Phantoms of the hand

Almost all amputees experience phantom phenomena of some sort after limb amputation [85, 86]. The phantom phenomena has been defined as "an awareness of a non-existing or deafferented body part with specific form, weight, or range or motion" [87, 88]. A French military surgeon named Ambrose Pare is credited with the first reported phantom phenomena following amputation in the 16th century [89] and Mitchell is credited for coining the term phantom [88]. Even people who are congenitally limb-deficient or who suffer a limb amputation at an early age may experience phantom phenomena [90]. Phantom phenomena come in a wide variety. They can present as a general awareness of the existence of a body part also termed phantom limb awareness [86]. A sense of movement of the phantom or feeling the phantom limb fixed in a certain position is also reported [88]. Telescoping is another reported phenomena manifesting itself as "shrinkage" or shortening of the phantom limb to the end of or within the residual limb [85]. Amputees may also experience specific non-painful somatic sensations such as tingling, itching, pressure, warmth or cold also termed phantom limb sensations [86]. Pain, occurring after an amputation that appears to originate in the missing limb (phantom limb pain) or in the residual limb (stump pain) are also frequently reported [86]. Furthermore, amputees may experience referral of sensation into the phantom limb after stimulation of various body parts [8, 91]. These referred sensations as reported by Ramachandran were modality specific, e.g. warmth was felt as warmth and the same for cold and vibrations. In a recent study, 12 out of 18 forearm amputees experienced the "hand-map phenomenon" in that touches on specific localized parts of the residual limb elicited somatic sensations in at least one specific phantom digit [9]. Some individuals exhibited a very detailed map where several separate areas of the phantom hand can be detected on the residual limb while in others the hand-map is less distinct or even non-existent [9]. Ramachandran [92] has suggested that referred phantom sensations are caused by the plastic reorganization of the primary somatosensory cortex that occur after amputations and that the phantom sensations can sometimes be produced by stimulating parts of the body that, while remote from the residual limb are located on body parts that are represented by cortical zones adjacent to the deafferented representation of the amputated limb. For example, the face and upper limb representations share a direct border in the primary somatosensory cortex and touch applied to the face can produce referred phantom sensations in the phantom hand. In contrast, other authors have suggested that other structures such as the thalamus, secondary somatosensory cortex, posterior parietal cortex and prefrontal cortex might be contributing to the phenomenon [93]. Furthermore, referred phantom sensations can sometimes be elicited by stimulating body parts that are not represented by adjacent zones in the primary somatosensory cortex, such as the lower limb in upper limb amputees [93, 94]. Di Pino *et al.* [95] review the above mentioned plasticity changes and what their impact could be for control and sensory feedback in prosthetic hands.

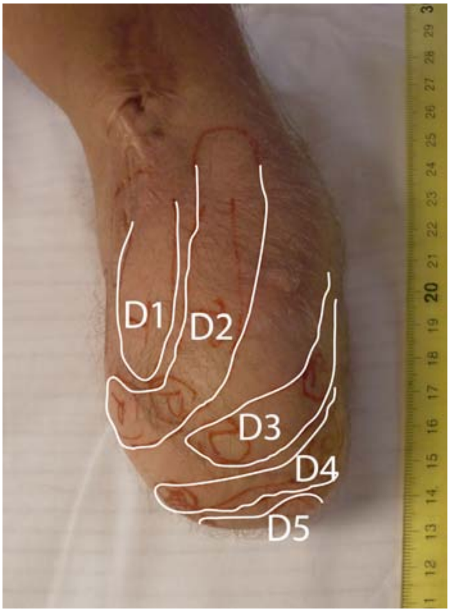

Figure 4.2: Phantom hand map on the residual limb of an amputee.

5

Sensors and sensory feedback systems

The need for a sensory feedback system in prosthetics has been discussed at great lengths [96–99]. Mann [96] noted in 1981 that "sensory feedback remain the most refractory of problems". This is still true today. A key finding in a survey study on upper limb prosthetics by Biddiss *et al.* [2] was that greater sensory feedback was of interest for all prosthesis users and particularly to those using active prostheses. Sensory feedback was reported by Kyberd *et al.* [6] and by Pylatiuk *et al.* [7] as a primary area of improvement in upper limb prosthetics. Ohnishi *et al.* [100] wrote in a review article, on neural machine interfaces for controlling multifunctional powered upper limb prostheses, that "enhanced sensory feedback is a critical issue for improved control, overall function and user acceptance". There are no prosthetic hands today that deliver sensory feedback in a conscious way to the user. Research efforts into making systems that operate in symbiosis both in intent and perception has been underway since the middle of the last century [101]. Several systems have been developed that differ in terms of what type of sensations they provide. Childress [102] made the division into different informational pathways, A, B and C (see Fig. 5.1). Pathway A consists of feedback signals that are visual or auditory and they are present in most prosthetic systems except those used by the blind or deaf. Pathway B consists of somatic sensory signals (e.g. tactile, proproception, temperature) and they are directed either to the surface of the body on the skin, where mechanical vibrations or electrical stimulation of the skin are the most commonly used methods, or directly to peripheral afferent nerves. Pathway C consists of feedback that is usually intrinsic to the prosthesis control system, using sensors in the prosthetic hand to automatically adjust the grip force.

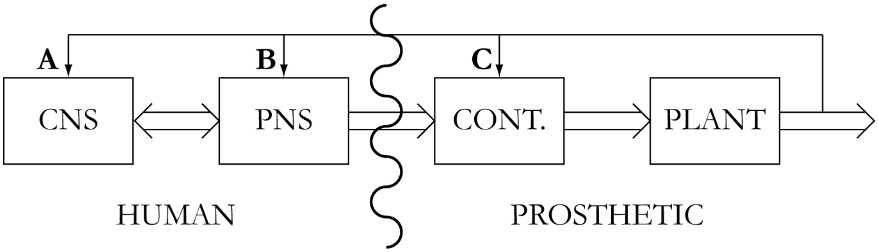

Figure 5.1: Diagram of different types of sensory feedback systems. A: Visual/Auditory feedback or direct stimulation of the CNS, B: Skin or peripheral nerve stimulation, C: Intrinsic feedback between the hand and the controller. (Redrawn from [102], © IEEE)

5.1 Sensors for prosthetic hands

There are many possibilities to endow a prosthetic hand with sensors to measure different parameters and to present the information to the user though different means of sensory feedback systems (Type A and B in Figure 5.1) or to use the information for an intrinsic control system (Type C in Figure 5.1). The latter approach is used in Otto Bock's SensorHand Speed which has an option for automatically adjusting the grip force using a slip sensor (SUVA) [103]. A similar method was used with the single-degree of freedom Southampton hand system using a "vibro-tactile" sensor [104]. Tura *et al.* [105] proposed an optical sensor for detecting movement of an object and prevent slip.

In a review article by Chappell [106], different sensor types for prosthetic hands are reviewed in terms of their range, specifications and characteristics. It is stated that the main types of sensors required in an artificial hand are force, finger position, object slip and surface temperature. A force sensor should be able to resolve forces up to 100 N with a frequency response over 100 Hz, position sensors should have an angular range of 120° with a frequency response over 100 Hz and slip sensors should have a maximum slip velocity of 1 m/s with a frequency response over 1 kHz.

Force sensors

There are a number of methods to measure force at the fingertips of a prosthetic hand. One method is to use strain gauges. Strain gauges have been used on the Cyberhand [30] and the SmartHand [28, 29] to measure the cable tension on cable driven fingers. Force sensors based on the Hall effect have been used on the MANUS hand [37, 38]. Force sensitive resistors (FSR's) have been used by Kyberd *et al.* on the MARCUS hand [107], by Tura *et al.* [105] and Murguailday *et al.* using an Otto Bock hand and by Davalli *et al.* [108] and Lundborg *et al.* [109] using a myoelectric prosthesis. A capacitive sensor has been suggested by Chappel *et al.* [110] capable of measuring forces up to 20 N. Optical sensors have been used on the SmartHand [28, 29], the Cyberhand [111] and the KNU hand [112].

Position sensors

To measure joint angles Hall effect sensors have been used in the SmartHand [28, 29], the CyberHand [30], the RPP intrinsic hand [44], the MANUS hand [37, 38], the Vanderbilt University Hand [26] and by Murguailday *et al.* using an Otto Bock hand [113]. If a finger of a prosthetic hand is fixed and has only one pivot point, the position of the finger can be measured directly using a rotary potentiometer in the joint or using a digital/rotary encoder on the motor driving the finger to infer the position.

Slip sensors

Miniature microphones can be mounted in a fingertip and are able to detect the audible noises made between two surfaces. This method has been used by Lundborg *et al.* [109] and could possibly also be used as a slip sensor. Using a polymer, PVDF, which has piezo-electric properties a slip sensor can be manufactured [114]. Another way, using thick-film technology to produce a slip sensor has been suggested [40, 41]. A piezoelectric sensor has also been used by Rodriguez-Cheu *et al.* to detect slip [115] and they have also suggested the use of an accelerometer for the same purpose [116]. Sensor arrays comprised of e.g. FSR sensors [117] can be used to indicate changes in a force map and from these changes, slip can be detected. Otto Bock integrated the SUVA sensor, a tri-axial force sensor, into their SensorHand to detect slip [103].

Temperature sensors

Temperature sensors in prosthetic hands have been explored by Davalli *et al.* [108] using thermoresistors. Cranny *et al.* [40] also included a temperature sensor in the form of a thick-film thermistor paste to monitor the temperature of held objects and to provide temperature compensation for the various other force sensors. Another sensor system, the BioTac, capable of detecting temperature, vibrations and force has been developed [118–120] and could prove useful in prosthetic hands.

5.2 Sensory feedback systems for prosthetic hands

There are several sensor options possible for integration in prosthetic hands capable of relaying information about force, position, slip and temperature. Most often sensors are used in a prosthetic hand to automatically regulate the grip force (Pathway C in Figure 5.1) without having the user in the loop. In order to create prosthetic hand systems that enables the prosthesis to be experienced as a part of the body, the user needs to be brought in to the loop, that is providing the user with sensory feedback. This will also make the user able to regulate the grip force according to what is sensed.

The mechanoreceptors in the hand code for four aspects of a stimulus: type (modality), intensity, location and duration. Sensory feedback systems for prosthetic hands do not always follow this distinction. Most of the proposed sensory feedback systems exploit the idea of sensory substitution where the feedback is delivered in a different modality or to a different location on the body [121]. For example, mechanical vibrations or electric currents are used to code for the force of a grasp. The types of sensory feedback systems that have been applied in prosthetic hands research can be broadly categorised as invasive and non-invasive systems, where invasive systems constitutes those that usually stimulate peripheral nerves or the cortex, and non-invasive systems are those were the stimulation is presented superficially on the skin. Furthermore, the non-invasive systems can be categorised as follows: Vibrotactile SFS, where a mechanical vibration is presented to the skin of the user and the frequency or amplitude of this vibration codes for e.g. the force of a grasp. Electrotactile SFS, where an electric current is passed through the skin and the amplitude or frequency of the electric current codes for the force of a grasp. Mechanotactile SFS, where a force normal to the skin is exerted and this force codes for the force of a grasp. Yet another way for sensory feedback is the use of sense substitution where a different sense codes the force of the grasp (e.g. force to auditory stimuli). This is also the case in Type A feedback where the amputee uses the sounds of the motor to infer position or force of a grasp.

Vibrotactile sensory feedback systems

Vibrotactile sensory feedback systems, where a mechanical vibration of the skin is used to convey the sensory information was proposed in a patent by Conzelman *et al.* in 1953 [122] and these systems have been further explored since the 1970's.

Back-Y-Rita *et al.* [123] proposed a Tactile Kinesthetic Substitution System (TKSS) based on their existing Tactile Vision Substitution System (TVSS) [124], where goniometers mounted at each joint or small shoulder-mounted television cameras controls a pictographic display on an array of (vibro-) tactile stimulators. A more economical format was also proposed where the elbow angle (α), the angle of pro/supination angle (β), the wrist flexion/extension angle (γ), the angle between fingers in opening/closing of a prosthesis (δ) and the finger pressure (π) would be fed back to the user. The angles (α, β, γ, δ) would be encoded in "bands" of tactile stimulators running down the upper arm or wrapped around the upper arm where a large angle would be indicated by activation of the two outer stimulators on a band. Finger pressure (π) would be encoded using frequency modulation on a single tactile stimulator.

Kato *et al.* [125] describe a sensory feedback system for the Waseda Model No. 4 hand which uses vibrotactile feedback. A pressure transducer attached to the tip of the index finger is used to modulate the amplitude of 100 Hz sine waves which is transmitted to the skin as mechanical vibrations. This model did not prove to be satisfactory and it was not fitted to amputees. The authors cite one of the problems as being due to the deterioration of the feedback function due to the adaptation of skin sensation to the vibrotactile stimuli.

Mann *et al.* [126] detail a sensory feedback system for the Boston Arm. The elbow angle is measured and fed back using a vibrotactile display with two stimulators. Von Bekesys phantom position phenomenon [127, 128] was used to encode the location of the stimulus. This generates a perceived stimulation of constant apparent loudness on the skin whose location between the fixed stimulators corresponds to the elbow angle. One amputee took part in the study where a conventional mechanical cable-operated elbow and the Boston elbow were compared. The results suggest that the Boston elbow with sensory feedback achieved similar results as the mechanical cable-operated elbow.

Pylatiuk *et al.* [129] tested a single-site vibrotactile stimulator placed on the prosthetic hand itself or on the residual limb of five amputees. A myoelectric hand with a FSR sensor placed on the prosthetic thumb was used in the tests. The grasp force was measured using the sensor and fed back using frequency modulation. The task evaluated was object lifting without visual feedback and it was found that the required grasping forces were lower when feedback was available.

Chatterjee *et al.* [130] report on a haptic feedback stimulator using vibrotactile stimulation with a prosthetic hand equipped with a strain-gauge placed on the thumb of a myoelectric prosthetic hand. Eight able-bodied subjects took part in the tests using an interactive force matching task. Visual and vibrotactile feedback was compared and visual feedback of force was shown to improve user performance at all force levels, whilst vibrotactile feedback led to improved performance in an experienced subgroup.

Sears *et al.* [131] detail a vibrotactile sensory feedback system for the MotionControl hand and ETD. Tests on non-amputees show a reduced error when using the vibrotactile sensory feedback system. Field trial using the hands and ETD's over two years are reported and the clinical advantages are said to be better control of the grip force and safer operation of the high strength ETD's.

Cipriani *et al.* [132] used a vibrotactile sensory feedback system consisting of one stimulator in combination with the Cyberhand [30]. Different EMG-control strategies based on finite state machines were evaluated together with visual and vibrotactile feedback on 14 able-bodied subjects in pick, reach and lift trials of several common objects. A single-site feedback paradigm based on frequency modulation was used. Subjective results were gathered in the form of interviews and objective results were obtained using grasp success percentages. Subjects reported that the feedback system does not physically disturb them and most of the subjects think it is useful during grasp tasks. No statistical differences were found between using the feedback system or not since the participants were always able to use visual feedback and roughly stopped the closure of the fingers when they had reached the object to be grasped.

Saunders *et al.* [133] describe a method in which an array of eight vibrotactile stimulators running down the length of the forearm and confined in a socket was used. Twelve able-bodied subjects took part in the experiments involving a TouchBionics i-Limb pulse hand controlled using FSRs. Grasp force was measured on the object to be grasped and fed back as position encoded stimuli (weak forces near the wrist and strong forces near the elbow). Using a grasp economy framework (appropriate assignment of grasp forces to objects of different weight) it was found that trained subjects perform economical grasps regardless of feedback. However, when uncertainty was introduced in the feedforward controller it was found that after training either vision or tactile feedback was sufficient to enable the task to be performed.

Cipriani *et al.* [134] detail a multi-site vibrotactile sensory substitution system to be used with artificial touch sensors in multi-fingered prostheses. Each vibration element (vibel) consisted of three vibration motors. In order to increase the total vibrational amplitude of the vibel, a method of constructive interference was used. Experiments using able-bodied participants were undertaken to investigate amplitude discrimination, frequency/amplitude combinations and sites and pattern discrimination. Results showed that able-bodied subjects were able to discriminate three amplitude levels with a success rate of 75%, to discriminate between three different locations with a success rate of 90% and to discriminate combinations or patterns (to be linked with grasp combinations) with a success rate of 78% among six patterns.

Electrotactile sensory feedback systems

In electrotactile (also termed electrocutaneous) sensory feedback systems an electrical current is passed through the skin to transfer sensory information.

Beeker *et al.* [135] detail a sensory feedback system for artificial touch in hand prostheses using a single site stimulator. The thumb of a prosthetic hand is equipped with a crystal sensor, which when bent will produce a voltage. This voltage will in turn be used to amplitude modulate a sine wave of 5 kHz between 1 and 5 mA and this will be used as the feedback signal.

Rohland *et al.* [136] describe an electrotactile sensory feedback system, where the thumb of an Otto Bock hand was equipped with strain-gauges. Direct current pulses with a pulse width of 0.1 ms and frequency of 1 kHz were amplitude modulated to convey the electrotactile sensory feedback. Formal tests using this system on able-bodied subjects, performing a task where a certain discrete pressure was applied to a pressure-measuring device using the system with feedback, without feedback and with their normal hand. The results showed that the mean squared error was ten times smaller when using the feedback system compared to not using the feedback system but also up to three times larger than with the normal hand.

Prior *et al.* [137], report on research made on electrocutaneous feedback for artificial limbs. They describe methods of encoding sensory feedback parameters in single and multiple electrodes and describe optimum parameters both from an information transfer and comfort standpoint. A pulse repetition rate between 1 and 15 pulses per second, a pulse width between 10 to 200 μseconds and an electrode current from 1 to 7 mA is suggested. It is also described how several parameters can be encoded on a single electrode. A 2-DoF (hand and elbow) proportionally controlled externally powered arm prosthesis with sensory feedback for hand opening and grasp force is described. An experimental 4-DoF (hand, wrist rotation, elbow, humeral rotation) is also detailed in which sensory feedback is proposed to contain grasp force, hand opening, wrist and elbow position, wrist and humeral future states and possibly limb loading force.

Prior *et al.* [138] further report on their research on electrotactile sensory feedback. It is stated that the addition of supplemental sensory feedback to the user does not guarantee an increase in performance unless two conditions are met: the ability to control the prosthesis must be limited by the lack of knowledge about the state of the prosthesis, not by the ability to generate accurate control motions, and the sensory feedback system must provide new information to the user. Three different supplemental sensory feedback systems are described : a single electrode system encoding hand opening using pulse repetition rate or pulse width modulation, a two electrode system encoding grasp force and hand opening using pulse repletion rate modulation and a four electrode system encoding grasp force and hand opening. In the four electrode system a combination of pulse rate modulation and selection of electrode (spatial selection/modulation) makes it possible to achieve a greater resolution.

Shannon [139] made a comparison between electrotactile and vibrotactile sensory feedback systems. It was shown that the sensory information transfer capabilities of both systems were similar. The electrotactile sensory feedback system had the advantage that it would reduce the number of components in a myoelectric control system whereas the vibrotactile sensory feedback system had the advantage of universal psychological acceptance.

Brittain *et al.* [140] report on an electrotactile sensory feedback system that uses strain-gauges in the index finger to measure pinch force. Feedback is consequently provided as short pulses of current which are frequency modulated proportionally to the pinch force. A case report is provided on a congenital amputee who had used the system and it is reported that the system provided the patient with a sense of competence and confidence she never had without it.

Shannon [141–143] details an electrotactile sensory feedback system to be used with a myoelectric prosthesis. Strain-gauges are fitted to the index finger of the myoelectric hand to measure the grasp force. Sensory feedback is provided as 10 ms bursts of 2 kHz pulses and the repetition rate of the bursts code for the sensory feedback where a low repetition rate codes for light touch and a high repetition rate for a strong grasp. Furthermore, ideas on how to gate the sensory feedback signal in order to have a working myoelectric system are explored. Two below-elbow amputees were fitted with the system and it is reported that the performance of the limb is enhanced by the presence of sensory feedback.

Agnew *et al.* [144] compare the functional effectiveness of a myoelectric prosthesis with electrotactile feedback to that of a split-hook prosthesis on a single amputee. The system used was that described by Shannon [141–143]. Several functional tests were performed and the results showed that the efficiency of the split-hook prosthesis was better than that of the myoelectric prosthesis with electrotactile sensory feedback.

Agnew *et al.* [145] describe further testing and training protocol in which patients were taught to produce myoelectric control signals and how to interpret the sensory feedback of the system described in [144] on four amputees. A range of subjective opinions from the users are reported. No comparison between a myoelectric hand with and without the system is made.

Boosfeld *et al.* [146] and Wang *et al.* [147] detail a sensory feedback system for the Tsinghua hand. It consists of four strain-gauges placed on a linkage bar between the thumb and index finger to sense the grasp force. The parameters of the electrotactile feedback system are identical to those suggested by Shannon [143] with a stimulation current between 2-10 mA, pulsewidth of 10 ms, pulse repetition modulated between 0-10 Hz and pulse composition of 2 kHz pulses.

Lundborg *et al.* [109] report on an electrotactile sensory feedback system using force sensing resistors (FSR's) on the pulps of the fingers and stimulators placed on the upper arm. Two methods of electrical stimulation were tested, one using repetition rate modulation and one using amplitude modulation. It was concluded that amplitude modulation was the better choice. Four patients with nerve injuries and one amputee using a myoelectric prosthesis took part in the experiments to evaluate spatial resolution, regulation of power in a grip and estimation of pressure magnitude. In the spatial resolution task two sensors were used (index and long finger) and the amputee was able to discriminate location in all trials. In the regulation of grip force task the patients were capable of regulating the force to predefined levels and in the differentiation between pressure levels the amputee was able to identify eight out of ten filaments in consecutive trials.

Yoshida *et al.* [148] describe another type of electrotactile sensory feedback system based on interferential currents. Two sine waves were used to synthesize a low frequency wave. Eight able-bodied participants took part in the experiments where one frequency was fixed at 4 kHz and the other was changed from 3.7 kHz to 4 kHz creating a resultant wave of 0-300 Hz. One of the reasons to use higher frequencies is that skin impedance is lower at higher frequencies. It is proposed that the frequency of the second channel should decrease with an increase in grasp force and vice versa.

Sasaki *et al.* [149] detail a similar setup as Yoshida *et al.* [148] using interferential currents. The stimulators were placed on the upper arm of nine able-bodied volunteers. In this work one of the frequencies was fixed at 5 kHz and the other was swept from 2 kHz to 4.9 kHz. Using a 1 kHz low-pass filter they showed that the interferential current setup could be used without interfering with the EMG signal. Using a high rate of change of the frequency of the second stimulator most of the subjects were only able to detect a difference once or twice. Using a lower rate of change enabled the participants to get a higher detection rate.

Geng *et al.* [150] describe a study on the effects of electrotactile stimulation patterns on the perception threshold. Five different electrode sites on the upper arm of 12 able-bodied subjects were used. Parameters including stimulus location, number of active electrodes, number of pulses and the delay between two pulses at different electrodes were investigated using biphasic, rectangular pulses. The results showed that in order to maintain a consistent perception threshold dual-channel stimulations using more than five pulses with an interchannel delay of more than $500\mu s$ should be used.

Mechanotactile sensory feedback systems

In mechanotactile sensory feedback systems a normal force or pressure is used to convey the sensory information.

Meek *et al.* [151] report on a system using direct force feedback using a single motor-driven pusher. Strain-gauges were placed on the fixed finger of a modified Dorrance-cable driven hook. Ten able-bodied subjects took part in grasp and lift tests to evaluate the sensory feedback system. EMG signals from the flexor muscles were used to close the hook and EMG signals from the extensor muscles were used to open the hook. The percentage of successful manipulations increased with the sensory feedback system, but the manipulation time did not decrease. It is stated that this is due to the myoelectric control system and not the ability to sense grip force.

Patterson *et al.* [152] describe a system using a stimulus cuff able to produce vibrotactile and pressure sensory feedback. The cuff was placed on the upper arm and a sensor using a PVDF piezoelectric film was placed on the finger of a robotic hand. EMG signals from the biceps and triceps were used to control the robotic hand. 25 able-bodied subjects took part in the experiments and were divided into five groups using different feedback modalities (vision only, pressure only, pressure and vision, vibration and vision). A reference and replication gripping test using a wooden block was used for all the feedback modalities. When using a single modality it was shown that vision produced lower errors than vibration or pressure and when using dual modalities it was shown that vision and pressure produced the lowest errors.

Sensinger *et al.* [153] tested a control group of ten persons and three amputees (two shoulder disarticulated, one transhumeral amputee), having undergone targeted reinnervation surgery [154], on how well they could discriminate gradations in force. A single Kinea Designs tactor [155] was used to apply a normal force to the skin. It was shown that the reinnervated chest area had near-normal sensitivity compared to the contralateral normal skin.

Panarese *et al.* [4] describe a system where tactile feedback was delivered to the glabrous skin of toes that have mechanical and neurophysiological properties similar to the fingertips. Using a grasp-and-lift task, in which able-bodied participants controlled two opposing digits of a robotic hand (the Cyberhand prototype) by changing the spacing of their index finger and thumb, it was shown that within a few lifting trials, all the participants incorporated the sensory feedback received by the foot in their sensorimotor control of the robotic hand.

Invasive sensory feedback systems

In invasive systems the sensory feedback systems are directly stimulating the afferent nerves.

Clippinger *et al.* [156] describe a system with an implanted stimulator using a inductively coupled RF receiver. A cuff type electrode where wires are wrapped around the nerve was used and connected to the implanted stimulator. A cable controlled hook with strain-gauges on the stationary finger of the hook was the intended use. Nine amputees were implanted with the device and a frequency modulated stimuli was used. All of the participants reported an increasing vibration with frequencies between 0-35 Hz and with frequencies over 35 Hz different perceptions were reported.

Reswick *et al.* [157] tested a system for sensory feedback using intraneural electrodes on one amputee. The electrodes were placed in the median and ulnar nerve above the elbow and carbon buttons connected to the electrodes were used to provide percutaneous passage. The amputee felt no sensation prior to activation of motor units and the sensation felt subsequently was that of tightening of muscles. A cable operated APRL voluntary closing hook equipped with transducers to measure force and position was used in the experiments to determine the difference in size of wood cubes with and without feedback. There was no significant difference in test scores with and without feedback. The conclusion was that the amputee gets enough feedback through the cable and the amputee ignores the electrical feedback provided.

Anani *et al.* [158] investigated direct stimulation of afferent nerves using fine wire electrodes in the superficial branch of the radial nerve on 11 able-bodied participants. Between four and six levels of intensity were investigated using amplitude and frequency modulation of an artificial stimulus. Depending on the placement of the electrode and modulation type, sensations of intensity or spread of paresthesia could be obtained. Using amplitude modulation in a subgroup with a small spatial spread of paresthesia elicited the lowest correct recognition ratio and in a subgroup with a large spatial spread of paresthesia the highest recognition rate. Using frequency modulation gave similar results in both subgroups.

Anani *et al.* [159] further report on direct stimulation of a sensory forearm nerve in nine able-bodied participants. Amplitude and frequency modulation of a stimulus and tracking of five or forty levels, either slowly or rapidly, was undertaken. It was found that amplitude modulation was superior to frequency modulation in all aspects studied.

Almström *et al.* [160] performed in vitro experiments with a saline solution and in vivo experiments on an amputee to determine the minimal distance between stimulating intraneural electrodes and surface pick-up electrodes. The study showed that it is possible to apply electrical nerve stimulation for prosthesis sensory feedback at a distance greater than 60 mm from the surface electrodes without causing significant interference with a conventional myoelectric control system.

Dhillon *et al.* [66, 161] investigated the residual function in peripheral nerves of amputees using longitudinal intrafascicular electrodes (LIFEs). Eight amputees took part in experiments on both sensory feedback and motor control. Frequency modulated pulse trains with 500 ms duration were used to stimulate the nerves. Subjects were asked to assign open-ended numbers to the magnitude of the elicited sensation for each stimulus presentation. Tactile sensations were typically reported as touch or pressure to a fingertip. Proproceptive sensations were initially vague, but with practice they were brought into focus.

Dhillon *et al.* [67] report on tests using LIFEs on three amputees with a modified Utah Artificial arm. The arm had strain gauges in the thumb to measure force and a position sensor in the elbow. A logarithmic mapping from the sensors to the stimulus frequency was used and a select electrode was used for either position or force. A training paradigm with three and five different force or position matches with visual feedback was used. The evaluation, without visual feedback, was performed using an pinch force meter or matching the elbow angle using the contralateral arm. All three subjects could judge changes in indentation or force applied to the thumb sensor and the static position of the elbow joint of the artificial arm.

Rossini *et al.* [68] used thin-film intrafascicular electodes longitudinally implanted in peripheral nerves (tf-LIFE4) of an amputee. Each electrode has eight active sites and two ground electrodes. Four electrodes were inserted in the median and ulnar nerve (two in each) of a 26-year old transradial amputee. Rectangular pulses were delivered with a pulse frequency ranging from 10 to 500 Hz, current amplitude between 10-100 μA and pulse width between 10-300 μs. A mapping of the electrode sites was undertaken to determine which site was able to elicit sensations. Discrete tactile sensations were elicited from different electrode sites in three electrodes and all sensations were referred to the corresponding fascicular projections areas. Furthermore, a decrease in phantom limb pain was seen one week after the removal of the electrodes with a return to the same level as before implantation three months after the removal of the electrodes.

Other sensory feedback systems

The sense of hearing has been used as a sensory substitution system to provide sensory feedback for prosthetic hands and can be considered a Type A system.

Lundborg *et al.* [162] describe a method using condenser microphones applied to a glove to detect friction sounds. One microphone per finger was used and the sound was then transferred to earphones using different intensity levels to create a synthetic stereophonic experience allowing a spatial resolution of the sound and enabling the possibility to identify individual fingers. Experiments investigating spatial resolution and differentiation between textures were undertaken in nine subjects (one forearm replantation, three nerve injuries and five prosthesis users). Differentiation between three fingers with and without the sensory feedback system yielded a mean accuracy of 92% and 23% respectively, while differentiation between four textures yielded a 94% accuracy with the sensory feedback system and 31% without.

Gonzales *et al.* [163] proposed an audiotactile feedback system using sounds of a violin to convey the position of a simulated thumb and sounds of a cello to convey the position of a simulated index finger. The positions were encoded as notes within the C - major scale, where a low C corresponded to a completely bent finger and a high C to a completely straight finger. Experiment were conducted using the participants own finger motions captured using bending sensors to control the simulated fingers. Errors were introduced in the translation between the real and simulated finger movements. Their results showed that it is possible to use auditive feedback to convey artificial proprioceptive information.

In osseointegrated thumb prostheses a perception of tactile stimuli has been observed [164]. This "osseoperception" is not based on skin movements adjacent to the skin-penetrating titanium fixture, since the skin in this area is immobile. It is hypothesized that the phenomenon is based on transfer of tactile stimuli from the thumb to intraosseous nerves via the osseointegrated implant.

Wheeler *et al.* [165] proposed a haptic device that provides a sense of position and motion by inducing rotational skin stretch on the user's skin. Experiments were performed where the device was used to provide proprioceptive feedback from a virtual prosthetic arm controlled with myoelectric sensors on the bicep and tricep muscles in 15 able-bodied participants. Targeting errors in blind movements with the haptic device were compared to cases where no feedback was provided. Average errors were lower with the device than with no feedback.

6

Summary of papers

As can be seen in Chapter 5, various approaches of sensory feedback systems have been presented over the years but none of the proposed systems has yet been convincingly proven usable. Essentially all proposed sensory feedback systems for prosthetic hands have been sensory substitution systems, transforming force to vibrations or electric currents, or fed back on different body sites. In this thesis a new concept for providing sensory feedback is proposed. It makes use of the hand-map that is formed on the residual limb of amputees and matching the type of feedback (force to force). Feedback actuators in the form of digital servomotors or air-mediated pressure bulbs were used to provide both non-amputees and amputees with sensory feedback in several studies.

This thesis builds upon the work performed at the Department of Measurement Technology and Industrial Electrical Engineering. The work in the papers was funded by the European Commision (SmartHand), the Swedish Research Council, the Crafoord Foundation, Stockholm Brain Institute, the Promobilia Foundation and Skåne County Council Research and Development Foundation. The following section outlines and summarizes the papers that can be found in the back of this book.

Paper I: SmartHand Tactile Display : A new concept for providing sensory feedback in hand prostheses
Antfolk C, Balkenius C, Rosen B, Lundborg G, Sebelius F.
J Plast Surg Hand Surg, 2010; 44: 50-53.

In this paper, a first evaluation of a new sensory feedback concept is presented. Experiments were performed on 11 able-bodied subjects. The experiments included discrimination of site of stimuli (three and five sites) and pressure levels on a single site. The sensory feedback system was a tactile display on the forearm composed of five servomotors (corresponding to having one sensor per finger of a prosthetic hand). The feedback actuators were placed in a U-shape on the forearm, reflecting the shape of a human hand (see Fig. 2.4).

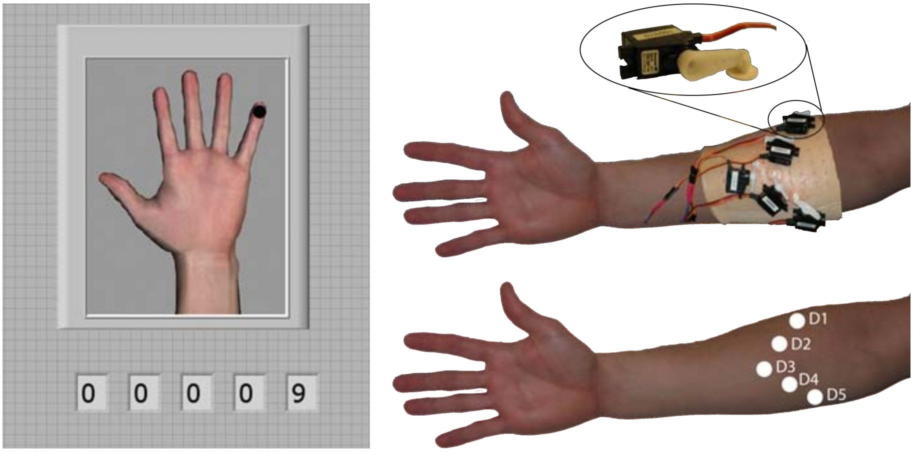

Figure 6.1: Computer interface for the tactile display (left) and actuator placement on the forearm of non-amputees (right). Reprinted with permission from Informa Healthcare.

After a learning period the participants were able to discriminate between three sites with an accuracy of 97%, between five sites with an accuracy of 82% and between five levels of pressure on a single stimulation site with an accuracy of 79%.

Paper II: Design and technical construction of a tactile display for sensory feedback in a hand prosthesis system
Antfolk C, Balkenius C, Rosen B, Lundborg G, Sebelius F.
Biomed Eng Online, 2010; 9: 50.

This paper reports on the technical design of a five site sensory feedback system. Control electronics and a test application for evaluating the sensory feedback system were further refined. A user interface allowing for different control options was developed. Furthermore, the system can be connected directly to sensors in a prosthesis or though a serial bus (see complete block diagram of the tactile display in Fig. 6.2).

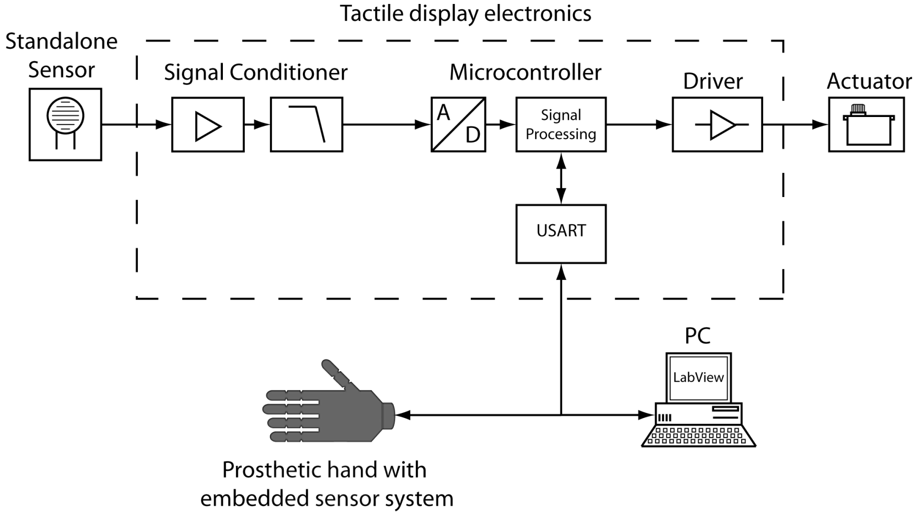

Figure 6.2: Complete block diagram of the tactile display system. The feedback actuators can be controlled through a PC, a prosthetic hand with an embedded sensor system or using stand-alone sensors.

As the servos used in the tactile display are position controlled, a position to force mapping was performed. This would allow a rudimentary control of force by using position and hence there would not be a need for force feedback sensors of the motors. Furthermore, as the system is intended to be used in myoelectric prostheses, artefacts in the EMG signal could be generated by the sensory feedback system and would interfere with the control system. EMG signals were recorded with the sensory feedback system in use and artefacts could be seen in the EMG signals. These artefacts could however be removed with a simple high-pass filter with a 20 Hz corner frequency. A cut-off frequency of 20 Hz should not reduce the performance of a myoelectric control system.

Paper III: Referral of sensation to an advanced humanoid robotic hand prosthesis
Rosén B, Ehrsson HH, Antfolk C, Cipriani C, Sebelius F, Lundborg G.
J Plast Surg Hand Surg, 2009; 43: 260-266.

In this paper, an investigation is performed to see if amputees can experience a "robot" like hand prosthesis as part of their own body. Most amputees experience a "phantom map" on the residual limb that when touched evoke sensations from specific fingers in the amputated hand. A goal for sensory feedback in a prosthesis is to provide a true perception of touch that gives a conscious sensibility to the user that results in a feeling of body awareness in the prosthesis. A modified version of the rubber hand illusion, using a "robot" like hand (the Cyberhand), was used to see if the illusion could be induced in amputees. Synchronous tactile stimulation was applied to the hidden residual limb and to the robotic prosthesis which the amputee could see. All five participants experienced the illusion. In two of the participants, who showed good motor control of the prosthetic hand, a motor control version of the rubber hand illusion was performed. In this scenario a moderate illusion could be observed. If brushing was added (i.e. combining both sensory feedback and motor control) a strong illusion was reported in one of the subjects.

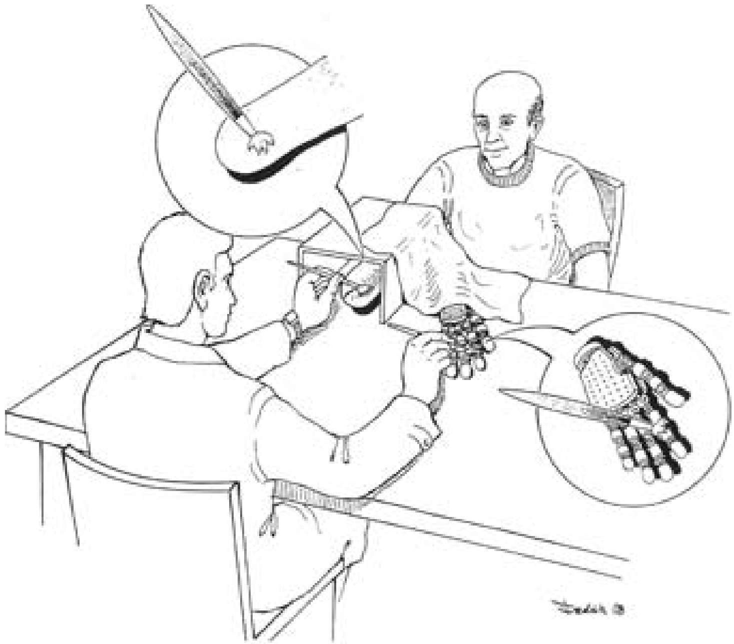

Figure 6.3: Experimental setup. Cyberhand prosthesis in full view and hidden residual limb being stimulated with a brush. Reprinted with permission from Informa Healthcare.

Paper IV: Transfer of tactile input from an artificial hand to the forearm: experiments in amputees and healthy volunteers
Antfolk C, Cipriani C, Carrozza MC, Balkenius C, Björkman A, Lundborg G, Rosen B, Sebelius F.
manuscript

In this paper, a comparison is made between non-amputees (n=5) and amputees (n=5) using three different sensory feedback tasks. The same hardware and software setup as the one described in paper II was used. The first task was to discriminate between five different localisations of feedback stimuli, the second task was identification of three different pressure levels on a single location and the final task was identification of a combination of the two in simulated functional grasp types. The positions of the feedback actuators were standardised in all experiments and for all participants (similar to the setup in paper I). Firstly the participants got acquainted with the equipment in a learning session with feedback. Secondly there was a relearning session where the participant was blindfolded and wearing sound-suppression head phones. After the presentation of each stimulus, the participant verbally indicated in which "finger" or at what level or as which grasp they perceived the stimulation and the test leader stated the correct answer, hence reinforcing the learning. Following this, there was a validation session similar to the previous session but without any verbal feedback. For the localisation discrimination task non-amputees got a correct score of 86% and amputees 76% in the final session. In the pressure level discrimination task non-amputees got a correct score of 98% and amputees 92%. In the final task, grasp discrimination, non-amputees got a correct score of 68% and amputees 59%.

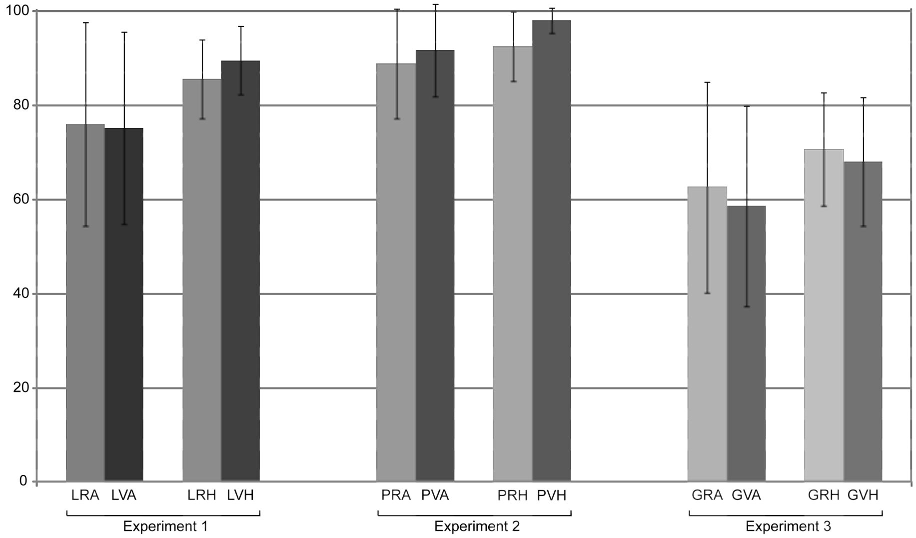

Figure 6.4: Results from the three different experiments.

Paper V: Sensory feedback from a prosthetic hand based on air-mediated pressure from the hand to the forearm skin
Antfolk C, Björkman A, Frank S-O, Sebelius F, Lundborg G, Rosen B.
manuscript

In this paper, an alternative solution for sensory feedback in prostheses is presented. A non-invasive simple sensory feedback system, which provides the user of a prosthetic hand with sensory feedback mediated by air in a closed loop system connecting silicone pads on the prosthetic hand with corresponding pads on the residual limb, was used. The silicone pads in this "tactile display" expand when their corresponding "sensor bulb" in the prosthesis is touched. Twelve trans-radial amputees and twenty non-amputees participated in the study. We investigated the capacity of the system to mediate detection of touch, discrimination between different levels of pressure and on the amputees also the ability to locate touch. The results showed a median touch threshold of 80 and 60 g in amputees and non-amputees, respectively, and 90 and 80% correct answers, respectively, in discrimination between two levels of pressure. The amputees located touch (three sites) correctly in 96% of the trials. It was concluded that this simple system has a potential to restore sensory feedback in hand amputees and it could thus be a useful tool to enhance prosthesis use.

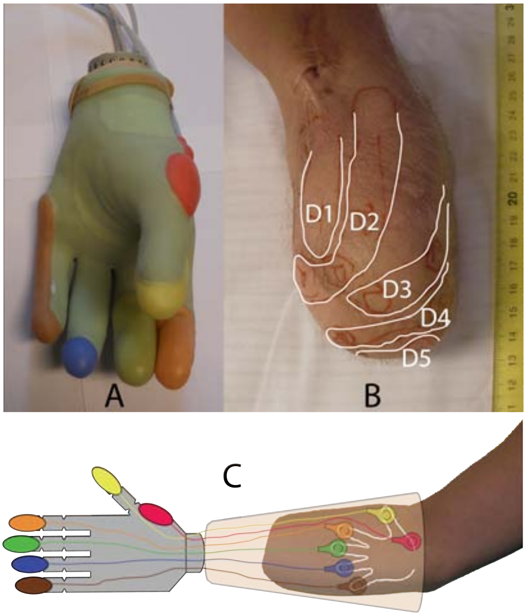

Figure 6.5: A : Otto Bock hand fitted with the sensor system, B : Phantom finger mapping of the amputee who took part in the study. C : Conceptual illustration of the whole system. Sensing bulbs on the prosthetic fingers to the left and actuating pads on the "phantom fingers" to the right.

Paper VI: Artificial redirection of sensation from prosthetic fingers to the phantom finger mapping on transradial amputees': a comparison study between multi-site vibrotactile and mechanotactile perception

Antfolk C*, D'Alonzo M*, Controzzi M, Lundborg G, Rosen B, Carrozza MC, Sebelius F, Cipriani C
* = equal contribution
manuscript

This work investigates whether vibrotactile or mechanotactile stimulation is preferable in a multi-site sensory feedback system for transradial amputees. A modality matched paradigm, using pressure to pressure feedback, and a modality mismatched paradigm, using pressure to vibrations, were compared. Eight transradial amputees took part in the study. Each of the sensory feedback systems was placed upon the phantom map of the participants to the extent possible. These findings show that placement of feedback devices on a complete phantom map improves multi-site sensory feedback discrimination and that the modality matched paradigm surpasses the modality mismatched paradigm for multi-site sensory feedback discrimination. Furthermore, subjects with a detailed phantom map had the best discrimination performance and even surpassed healthy participants for both feedback paradigms.

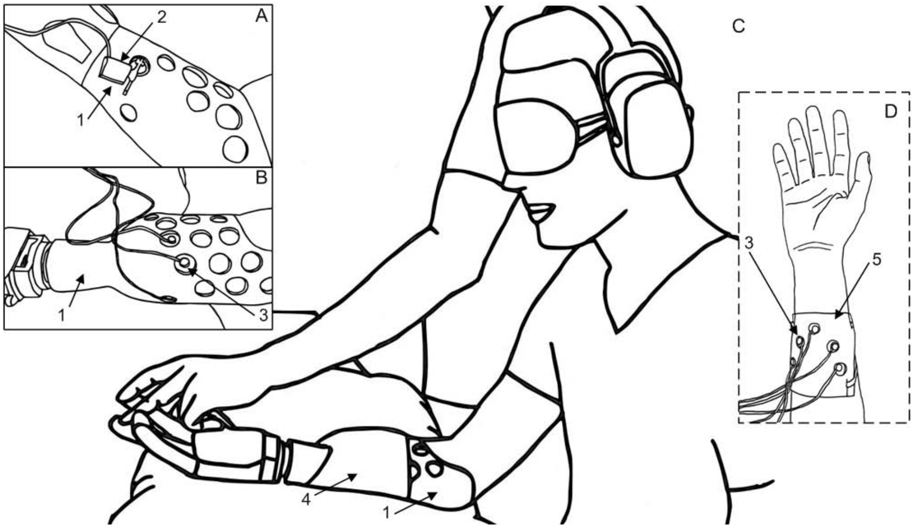

Figure 6.6: Placement of mechanotactile stimulators (2) and vibrotactile stimulators (3) in the customised socket (1). Participants held their residual limb in a supine position on the table during the whole experiment . Image courtesy of Marco D'Alonzo, Scoula Superiore Sant'Anna.

7

Discussion and outlook

As a first step in providing a more physiologically correct tactile sensory feedback from a prosthetic hand the following should be fulfilled: correct modality, correct somatotopy (using the phantom "hand map" if possible), correct intensity and correct duration. It should also be noted that the timing of the stimulus is of importance. As this is an artificial sensory feedback system the processing time and delays of actuators and sensors should be taken into account when designing such systems. Delays or temporal mismatching have shown to not elicit feelings of body ownership [166]. When using a modality and somatotopically matched sensory feedback system all four aspects of a stimulus can be coded for and thus provide a natural and physiologically correct sensation.

In this thesis a new concept for providing sensory feedback is proposed. It makes use of the hand map that is formed on the residual limb of amputees and matching the type of feedback (force to force). It was shown that amputees can learn to interpret sensory feedback on different locations and that the developed sensory feedback system would not interfere negatively with a myoelectric control system. Furthermore, it was shown that using modality matched feedback in a multi-site discrimination task yielded better results that using modality mismatched sensory feedback. Using a multi-site feedback system as the one proposed may also prove to have other benefits than providing an amputee with a natural feedback. Other research has shown that sensory feedback and discrimination of location of feedback reduces phantom limb pain [167, 168].

Using the phantom hand map of amputees seems like a promising paradigm in providing the amputee with feedback of sensation. However, the hand map in amputees vary greatly between individuals. Also, the actual map in the residual limb might be in such a position that it is not practically possible to place the feedback actuators optimally when making the prosthetic socket. Furthermore, a complete hand map is not always formed. In such cases it is probably best to use the map to the extent possible and if needed placing other actuators elsewhere. Others may exhibit a map where each finger from tip to base and also the palm of the hand is felt. In such cases perhaps a feedback actuator per phalanx might be appropriate. Feedback devices capable of multimodal sensory feedback is also an interesting future prospect.

It would be of interest to see what happens if an amputee was fitted with a myoelectric prosthesis having a sensory feedback system at the very first fitting after amputation. Furthermore, what would happen if a transradial amputee, at the time of the first surgery, underwent a targeted sensory innervation procedure. It also seems like very little is known about the sensory qualities of the hand map, its persistency and its true origin. Research endeavors in this area are likely to shed knowledge not only on the optimal way of giving amputees a sense of touch in their prosthesis but to give insights into the ever alluring inner workings of the human brain.

While multi-articulating artificial hands are no longer a future prospect, the control of such hands and the feedback of sensation is still lacking. Research has shown that it is indeed possible to control such hands in a much more sophisticated manner, but there is still a long way to go to a commercially and clinically viable system. Implantable devices that obtain information from intramuscular electrodes or directly interfacing with peripheral nerves, have an ever longer way to go, but some promising results have been presented. Problems of stability and biocompability issues need to be resolved and furthermore, such devices need to prove an added value to the user that outweighs the inherent risk of an implant. Another possible solution to the control problem would be to provide feedback cues when selecting a grasp, analogous to a P300 speller using EEG.

Another issue is how to properly evaluate an intelligent prosthesis system. Traditional outcome measures may leave a lot to be desired when it comes to assessing advantages or disadvantages of such systems. This is of very high importance as it is unlikely that the institution providing and ultimately paying for a prosthesis would prescribe such a device without ample evidence of its superiority.

Even though the topic of this thesis concerns sensory feedback for upper limb prostheses, much of it can be applied to lower limb prosthetics. Typically, lower limb prostheses are of a passive type, but in recent years computer controlled knee prostheses such as the Rheo-knee and Power-knee by Össur and the C-leg by Otto Bock have emerged. These types of lower-limb prostheses are not under direct volitional control, they rather sense gait patterns and comply to such. Research prototypes of a powered ankle-foot prosthesis [169] and powered knees [170] have been developed and myoelectric control of such devices has been proposed [171, 172]. Furthermore, the use of Targeted Reinnervation surgery on transfemoral amputees seem to be evident and likely imminent and such a procedure may introduce further control capabilities of lower limb prostheses. After a Targeted Reinnervation procedure certain sensory qualities may also be produced and providing lower limb amputees with sensory feedback could be useful in e.g. modulating the gait cycle.

8

Acknowledgements

After some five years at Elmät and in Sweden the end of this chapter of my life is nigh and I look forward to what the future will bring. I would like to extend my deepest and most sincere gratitude to my supervisors Thomas Laurell and Fredrik Sebelius, to my mentors and collaborators: Göran Lundborg, Birgitta Rosén, Anders Björkman, Christian Balkenius, Henrik Ehrsson and Sven-Olof Frank and to my collaborators in Italy: Maria Chiara Carrozza, Marco D'Alonza, Marco Controzzi, Gunter Kanitz and a special thanks to Christian Cipriani for all the support and numerous interesting discussions over Skype. Also, a deserved gratitude to the funding agencies is due: the European Commision, the Swedish Research Council,the Promobilia Foundation, the Crafoord foundation, the Royal Physiographic Society in Lund and Stockholm Brain Institute.

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9

Populärvetenskaplig sammanfattning

Denna avhandling behandlar ämnet känselåterkoppling i handproteser. Att mista sin hand är en traumatisk upplevelse och den som har mist sin hand förlorar både känsel och motorik. En rudimentär greppfunktion kan återskapas genom att använda en handprotes. Nya och avancerade proteser som kontrolleras med hjälp av muskelsignaler finns numera på marknaden och dessa myoelektriska handproteser möjliggör användandet av flera greppfunktioner. De avancerade myoelektriska handproteser som finns idag har inte någon känselåterkoppling som når användarens medvetande. Detta kan bidra till begränsat användande.

Känselåterkopplingens betydelse är flerfaldig. Man behöver känselåterkoppling för att kunna reglera styrkan i ett handgrepp. Vidare så kan känselåterkoppling från handprotesen eventuellt vara av betydelse vid behandling av fantomsmärta. I hjärnan finns en kartbild av kroppens alla delar. Vid en handamputation tas handens område i hjärnkartan snabbt över av underarmens område. Fingrarna känns nu i ett specifikt mönster på amputationsstumpen och magnetkameraundersökning visar att beröring av detta mönster registreras i hjärnans handkarta. Genom att använda detta mönster av fingrar som finns i amputationsstumpen för att återkoppla känsel kan en kroppsegen uppfattning av proteshanden framkallas. Tidigare utvecklade system inom forskningen har använt sej av vad som kallas "sensory substitution" eller känselersättning. I ett sådant system omkodas t.ex. tryck på en proteshands finger till vibrationer som överförs till ett annat ställe på kroppen.

Vi har utvecklat ett nytt koncept för känselåterkoppling i handproteser. Genom att använda sensorer placerade i fingerspetsarna på en handprotes och genom att ha små elektriska motorer eller ett system av luftbubblor som stimulerar huden på den amputerades underarm kan man få en handprotes att förmedla känsel. Undersökningar har utförts på icke-amputerade och amputerade. Vidare genom att specifikt stimulera det mönster av fingrar som de flesta amputerade upplever i amputationstumpen kan den amputerade få en verklig känselförnimmelse av varje finger. Eftersom känselåterkopplingssystemet är tänkt att användas i myoelektriskt styrda handproteser har vi också visat att systemet kan användas utan att negativt påverka de signaler som genereras av musklerna och används av styrsystemet. Ett helt passivt system (utan elektronik och batterier) har också utvecklats i vilket man använder luftbubblor som sensorer och stimulatorer. Detta system utvecklades för en myoelektriskt styrd protes men skulle också kunna användas i kosmetiska och kroppsdrivna system p.g.a. dess låga vikt. En preliminär undersökning av kroppstillhörighet har också genomförts i vilken man kunde se att amputerade kunde integrera en robothand i sin kroppsbild. Vi har också jämfört vårt system med ett system som baseras på känselersättning i form av vibrationer. I denna studie använde vi oss av det tidigare nämnda mönstret av fingrar en amputerad upplever på sin kvarvarande arm. Resultaten visade att det system som bygger på tryckstimuli var att föredra framför ett känselersättningssystem baserat på vibrationer. Fastän denna forskning har haft fokus på handproteser så skulle resultaten också kunna tillämpas på fot och benproteser. Även om våra undersökningar har visat goda resultat inom området för känselåterkoppling i handproteser finns det flera aspekter inom handprotesområdet som kräver vidare forskning och utveckling. En handprotes ska verka i symbios med sin användare och för att öka användbarheten så bör proteshänders mekanik, styrning och i synnerhet känselåterkoppling vidareutvecklas.

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