TTK4550 - Engineering Cybernetics, Specialization Project

Haptic Feedback for Hydraulic Hand Prosthesis

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Summary

This report is a study of haptic feedback for upper limb prostheses, and in particular related to the Norwegian company Hy5's hand. The report starts with a theory section about haptic feedback, sensors and actuators, human sensory systems in the skin and motor control. Then, the relevant aspects of the Hy5 hand are presented.

Three different architectures are then presented and discussed, before reaching a conclusion that a system based on sensors in the fingers of the prosthesis and actuators on the skin of the user is most suited. This architecture is chosen due to its versitility and adaptability. Future work includes building a prototype and validating if such a system could further increase the benefits of using the Hy5 hand.

Sammendrag

Denne rapporten er et studie av haptisk tilbakekobling for håndproteser, med spesielt fokus på det norske firmaet; Hy5, sin hånd. Rapporten begynner med en teoridel om haptisk tilbakekobling, sensorer og aktuatorer, sensoriske systemer i huden og menneskelig styring av bevegelse. Deretter blir de relevante delene av Hy5 hånden presentert.

Tre forskjellige arkitekturer blir så presentert og diskutert, før en konklusjon om at et system basert på sensorer i protesens fingre og aktuatorer på brukerens hud er best egnet. Denne arkitekturen ble valgt da den er enkel å tilpasse. Fremtidig arbeid arbeid inkluderer å bygge en prototyp og validere at et slikt system kan øke fordelene ved å bruke Hy5's hånd.

Problem Description

The Norwegian firm Hy5 AS develops hand prosthesis for people lacking a hand and/or part of an arm, either due to a congenital disorder or a traumatic amputation. To give the user the best possible conditions for controlling the motion of the prosthesis in an accurate manner, implementing a form of haptic feedback is desirable. Meaning that information about forces, velocities, and/or joint angles in the prosthesis are conveyed to the user through one or more ways of stimulation (mechanically or electrically), and thus in principle some of the mechano sensory abilities lost due to amputation is restored. Through this project, you shall explore and possibly test suitable sensor and actuator modalities as well as complete algorithms for the haptic feedback system.

- Provide an overview of terms and techniques within the field of haptic feedback in robotics and tele-manipulation in general, but with an added emphasis on earlier research related to upper limb prosthesis. The overview should cover the physiological structures (mechano receptors in the skin etc.) the equipment will interact with, and sensor and actuator modalities, and different algorithms and philosophies attempted in the past.
- Assess how compatible the findings from part 1 are in regards to the existing prosthetic system.
- Make a justified choice of architecture, algorithms and actuator and sensor technology for haptic feedback for the Hy5 prosthesis, and make an assessment of which aspects of the resulting system are most uncertain.
- To the degree which time allows, make a physical setup, demonstrating and evaluating the planned system. Priority should be given to the uncertain components of part 3 whenever a decision has to be made regarding what to implement and test.

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Abbreviations

EMG	=	Electromyography
CNS	=	Central Nervous System
PNS	=	Peripheral Nervous System
FA	=	Fast Adapting
SA	=	Slow Adapting
TMSR	=	Targeted Muscle and Sensory Re-innervation
MCU	=	Micro Controller Unit
FSR	=	Force Sensitive Resistor

CHAPTER

ONE

INTRODUCTION

1.1 Powered Upper Limb Prostheses

Prosthetic replacements of missing limbs, either due to amputation or a condition existing at birth, is an old medical technique. An early powered design can be found as 1915 Germany [10], where the prosthetic hand was powered by pneumatics. During the 1960s, using surface electromyography (EMG) on residual limbs became available for commercial prostheses, and is currently the most used source of a control signal in powered upper limb prostheses [20]. The EMG signal is produced by a contracting muscle or muscle group, and is detected by a set of electrodes placed on the users skin. While this gives the user a clear, if not direct, link from intent to prosthesis movement there is little flow of information the other way, other than incidental clues like motor noise and vibration.

1.2 Haptic Feedback

When providing haptic feedback to the prosthesis user, one can either attempt to stimulate with the same modality as is measured, or through some substitute channel. When the measured entity matches the modality used as feedback we say we use modality matched feedback. An example is a force sensor placed on the fingertip of a prosthesis digit which causes a linear tactor to impart a force in the users skin. Whenever the feedback is on a form that is different what is sensed, it is said that the feedback takes the form of sensory substitution, such as force levels represented as a vibration. Most research into the field of sensory feedback for upper limb prosthesis uses sensory substitution [3].

In addition to modality, the somatotopic matching, the perceived location of the stimuli, is important for the quality of the feedback to the user [15]. Most simple and early research into haptic feedback lacks somatotopic matching.

1.3 Motivation

Not having a hand reduces functionality. Not only the ability to manipulate physical objects, but also the ability to gather information about them is lost. Currently there are no commercially available powered upper limp prosthesis who supply the user with tactile or haptic feedback other than forces transferred through the prosthesis itself. Regaining some of the sense of touch can increase embodiment [18], reduce phantom pain [9] and increase the ability to use the prosthesis without using visual feedback [25]. All of these points combined can explain why users often cite haptic feedback, or lack thereof, as a reason for prosthesis abandonment [8].

CHAPTER

TWO

THEORY

2.1 Human Sensor Array

When a loss of limb occurs, several sensory functions are lost. For a healthy human, information about touch, proprioception, pain and temperature is transmitted from nerve endings in the skin, muscles and tendons of the hand and arm, through the peripheral nervous system (PNS), to the central nervous system (CNS), where the signal is interpreted and used.

2.1.1 Mechano Receptors

The glabrous skin found in the human hand contains several different types of nerve cells responsible for mechanical sensations, such as force, vibration and texture, temperature and pain. The focus of this paper will be the mechanical sensations, as they are the most closely related to the control input of the prosthesis and therefore the most useful when forming a closed loop control circuit.

There are four different classes of mechanoreceptors responsible for the mechanical sensations in humans. These differ in function, receptive fields and adaption rates. The different cells can be divided by their adaption rate, into fast adapting (FA) type I and II, and slow adapting (SA) type I and II. A summary of the different functions can be found in table 2.1, based on [16].

	Fast Adapting (FA)	
	Meissner corpuscles (FA I)	*Pacinian corpuscles (FA II)*
Receptive field	Small, sharp	Large, diffuse
Density $\left[\frac{\text{units}}{\text{cm}^2}\right]$	140	20
Spatial Resolution [mm]	3-4	10
Stimulation Frequency [Hz]	5-50	40-500
Sensory Function	Vibration detection. Temporal change in skin deformation.	High frequency vibration detection. Temporal change in skin formation.
	Slow Adapting (SA)	
	Merkel cells (SA I)	*Ruffini endings (SA II)*
Receptive field	Small, sharp	Large, diffuse
Density $\left[\frac{\text{units}}{\text{cm}^2}\right]$	70	10
Spatial Resolution [mm]	0.5	7
Stimulation Frequency [Hz]	0.4-40	<7
Sensory Function	Static force detection. Form detection. Texture perception.	Static force detection. Finger position determination Tangential force detection

Table 2.1: Overview of mechanoreceptors found in glabrous human skin. Adapted from [16]

The receptive field of a mechanoreceptor is the area of the skin where a nerve ending can detect stimuli, the density is the amount of cells pr unit of area, the spatial resolution is the smallest distance between two stimuli that will result in a "double" sensation, the stimulation frequency is the frequency range detectable by the receptor.

2.1.2 Proprioception

Proprioception is the sense of the relative position of joints and limbs of the body [24]. Information about muscle extension, tension in tendons and joint position is transferred from nerves within muscle, tendons, joints and skin to the CNS. In addition to the use by the CNS, proprioception is an integral part of human reflexes. This includes relaxing muscles when an overloading is detected and compensation for an abrupt increase in load [24].

2.2 Motor Control in Humans

During manipulative task, the time between an error episode and the corresponding corrective action is at least 45 ms, which will yield a maximum control signal frequency of 1 Hz, which is slower than many manipulation tasks [12], and thus motor control cannot only rely on continuous feedback control.

In [13], Johansson et.al. argues that the role of feedback in such a feed-forward system is to detect the transition of action phases; the different phases of manipulation task. The transitions of such phases takes the form of discrete events detectable by the PNS and in turn the CNS.

Johansson also argues that the tactile information is used to update internal models such that the same object or similar objects can be manipulated according to an updated feed forward scheme in the future. The theorised internal models include both the expected tactile feedback from external objects, as well as the feed-forward commands necessary to complete a desired trajectory of motion [14].

2.3 Sensors

The four mechanoreceptors discussed previously all respond to external forces, either normal forces or tangential forces. Based on their adaption rates and frequency ranges, they exhibit a varied sensitivity to vibration as well as to sustained pressure. There are also sensory organs responsible for detection and monitoring of relative joint position. The following section will outline different classes of sensors that can be applied to fulfil the task of the lost neural sensors. For reviews of tactile sensing see [31], [17] and [3].

2.3.1 Force Sensors

When gripping an object, sufficient force must be applied such that the friction force between the hand and object can overcome the pull of gravity. However, with coefficients of static friction varying by several orders of magnitude, the force required to lift and hold an object varies not only with the mass of the object, but also with its surface properties. This in effect creates a lower bound for the force to be applied. Objects to be held will also be crushed at different force levels, putting an upper bound on the force to be applied.

Strain Gauges

A strain gauge is a resistor, or set of resistors which resistive values change with deformation. Strain gauges are long resistors adhered to a plastic or plastic like film. When strain is applied to the strain gauge, the resistance across its two terminals changes. Strain gauges exhibit a high sensitivity, but are susceptible to noise from temperature change and humidity. To combat temperature sensitivity, a Wheatstone configuration is often employed. Strain gauges can be made with high spacial resolution and high sensitivity and are a well established technology.

Force Sensitive Resistor (FSR)

An FSR is a material which resistance changes with applied force and consists of layers of polymer materials. FSR's have a non-linear response, in that they show a higher sensitivity at lower applied forces [7]. While the FSR has a high degree of sensitivity, the variability is also high. Hysteresis is also present in an FSR. The FSR is also sensitive to noise from temperature changes [7].

An FSR can be made with dimensions at least as thin as $200\mu\mathrm{m}$ as well as flexible enough to be fitted around a prosthetic finger, and can be manufactured at a low cost [25].

Capacitive Sensors

A capacitve sensor can be made by mounting two capacitive plates with an isolating or dielectric material in between [19]. A known relationship between deformation and force and between deformation and capacitance can be exploited to measure the applied force. Capacitive sensors are generally accurate, sensitive and can detect both static and dynamic forces. They also consume little power. This comes at the cost of higher prices and a need for more complex electronics. [16]. Capacitive sensors can be made vary thin and with a small cross-section.

Optical Sensors

An optical sensor consists of a light source, a transduction material and a light detector. When light from the source passes through the transduction material, the light is modulated in proportion to the force or pressure applied to the transduction material [22]. Optical sensors require extra circuitry and are generally large and fragile. At the same time optical sensors yield a high spatial resolution and is close to immune to electromagnetic fields.

Piezoelectric Sensors

Piezoelectric materials generate voltages when deformed by an external force. This generate voltage can be used in a piezoelectric sensor to sense changes in forces. Such sensors are reliable, fast and require no external power-supply. However, by their nature only dynamic forces can be detected, and at a low resolution [16].

2.4 Actuators

In the following sections, four ways of creating a sensation of mechanical stimulation will be discussed. Vibrotactile, creating a mechanical vibration [4], electrotactile, stimulating the skin and nerves with electric pulses, normal force [16], pushing the skin via some actuator creating a force normal to the skin [23], and direct nerve stimulation where a stimulator is implanted under the skin to directly stimulate a nerve ending to emulate signals coming from mechanoreceptors [29].

2.4.1 Stimulation by Sensory Substitution

Vibrotactile stimulation

In vibrotactile stimulation, information of some state is conveyed to the prosthesis user via some vibrating actuator. By its vibrational nature, several physical aspects of the wave can be used to transmit information to the user. This includes frequency, amplitude and different wave-forms, with frequency and amplitude the most common information carriers.

To stay withing the frequency range of the fast adapting type II mechano receptors, see table 2.1, staying within $50 - 300\text{Hz}$, as recommended in [16], will achieve this.

Electrotactile Stimulation

In electrotactile stimulation, information is conveyed to the prosthesis user via a small, low power electrode. The application of either a controlled current or voltage on an area of the skin stimulates nerves close to the stimulation site creating a sensation of mechanical stimuli for the user.

The sensation created by electrotactile stimulation is reported as ”a tingle, itch, vibration, touch pressure, pinch, and sharp and burning pain depending on the stimulating voltage, current and waveform, as well as on the electrode size, material and contact force, and the kin location, hydration and thickness” [3].

By the electric nature of electrotactile stimulation, the generated voltage and current can interfere with EMG-sensors placed in close proximity to the actuators. To mediate this, extra filtering of the EMG signal or time multiplexing, i.e switching between stimulation and EMG detection, can be included in the prosthetic system.

2.4.2 Modality Matched Stimulation

Normal Force Stimulation

In vibrotactile stimulation, information of some state is conveyed to the prosthesis user via a linear actuator pressing down on the skin. A normal force stimulator can take the form of a motor driving a shaft onto the skin, but the required pressure can also be created by hydraulics or pneumatics.

Direct Nerve Stimulation

In direct nerve stimulation, an electrode is implanted to directly electrically stimulate the remaining nerves in the residual limb. In contrast to the previously presented stimulation techniques, direct nerve stimulation is highly invasive as it requires much closer access to the subjects PNS. By implanting a small electrode by or around an afferent nerve ending it is possible to start the propagation of an action potential.

By stimulating parts of the PNS directly, a layer of abstraction and cognitive load is clearly removed from the user. However, currently the signal perceived by user is often reported as feeling unnatural and foreign. This is thought to be caused by the fact that direct nerve stimulation stimulates a large section of nerve fibres and without consideration being taken in regards to the relative timing of their firing [13].

A way of minimising the inherent risks involved with having electrode wires piercing the skin is to fasten the prosthesis to the body via osseointegration [6], integrating a metal bolt into the skeletal system. Using the metallic connector for the prosthesis as a sterile and structurally sound way into the body could aid the viability of direct nerve stimulation.

2.5 Targeted Muscle and Sensory Re-innervation

To address the issue of somatotopic matching, targeted muscular and sensory re-innervation (TMSR) surgery may prove useful. In TMSR, motor and sensory nerves are rerouted from the residual limb to other parts of the body [27]. Thus, by moving the nerve endings from the residual limb to, for example the chest area, one can achieve somatotopic matching to a higher degree and also increase the possible areas of stimulation.

2.6 Phantom Limb Maps

As demonstrated in [11] by Ehrsson et. al. and exploited in [2] by Antfolk, many who have undergone an upper limb amputation experience that stimulation of specific areas of the residual limb cause a sensation of the missing limb being stimulated. The phenomenon is called a phantom limb map. A study, by Björkman et.al [5] showed that the same areas of the primary somatosensory cortex were activated when stimulating the phantom limb map as in a control group consisting of unimpaired individuals. For prosthesis users with a phantom limb map, either complete or partial, a higher degree of somatotopic matching can be achieved than without, and this is thought to increase ownership over the prosthesis and reduce the training time needed to effectively utilise the haptic feedback [2].

CHAPTER

THREE

HY5 HAND

Hy5 is a Norwegian company with offices in Raufoss and Oslo. At time of writing Hy5 offers a myoelectric prosthetic hand where the delivery of torque to the fingers is done via hydraulics. Through the use of 3d-printed and lightweight components, an adaptive grip where the digits of the fingers close in a natural fashion, and hydraulics, rather than an array of electric motors, Hy5 achieves a relatively high degree of functionality while maintaining robustness and keeping expenses down [28].

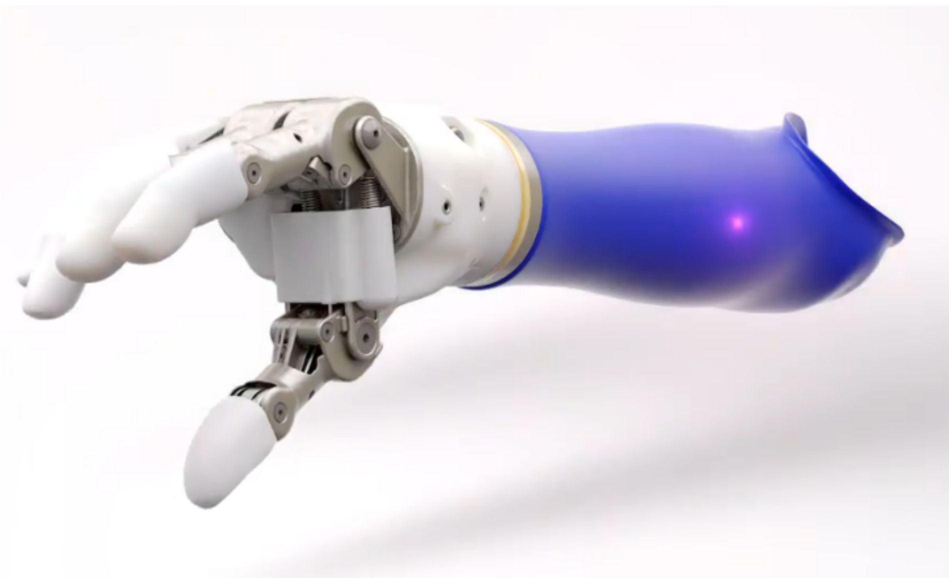

Figure 3.1: A computer generated illustration of the current Hy5 hand with a socket i blue attached.

3.1 Hydraulic system

The main difference between the Hy5 hand and other available prosthetic hands is the reliance on hydraulics. For a comprehensive look at the the design see the patent for the pump assembly [21]. The Hy5 hand employs a single electric motor driving a high pressure, low volume pump and a low pressure, high volume pump. By running the high volume pump until contact with an object and the subsequent build up of pressure, the hand can close with a high speed, but still achieve a high maximum gripping force due to the inclusion of two different pumps. Both pumps pumps fluid such that pressure builds up behind the middle finger, index finger and thump, however, when the hand has closed around an object, only the high pressure pump is in action.

3.2 Adaptive grip

The fingers are designed such that the force provided is balanced between the index and middle finger and the thumb. These three fingers have a secondary digit, distally, as an approximation of a normal human finger. When contact between a finger and an object occurs, the part of the finger, or the finger that made contact will stop its motion, while the pressure will be transferred to the other fingers, such that every finger will move until all are in contact. By a system of wires and springs, the top digit of a finger will keep moving should the bottom part reach an object.

This automatic and equal distribution of forces, combined with the finger digit design, allows the Hy5 hand to grasp a multitude of different shapes.

3.3 Current Control System

The Hy5 hand has one control input, which controls the speed of the motor. This, in turn, builds up pressure. The control input to the motor can be sourced from the difference between to antagonistic muscle groups, giving the user some control of the motor speed and thus of the pressure and torque produced.

The design of the fingers and their cable configuration, the hand is only able to provide significant force when closing. The opening of the fingers is provided by a configuration of springs in the fingers and by the opening of valves allowing hydraulic fluid to flow from the finger side of the hydraulic system.

CHAPTER

FOUR

METHOD AND PREVIOUS WORK

4.1 Literature Review

To gain an understanding of the subject at hand, a literature review was undertaken.

First, an understanding of the current state of myoelectric upper limb prosthesis was sought out. This is a mature field, with several commercial actors and a large literature bank, including books such as [20] by Muzumdar. The understanding gained consisted of understanding the origins of the myoelectric signal; the propagating action potential along a contracting motor unit. Then, when the source of the control signal was understood to a sufficient degree, an understanding of how the myoelectric signal can be used to control one or more states of a prosthesis was acquired.

After having gained a sufficient understanding of upper extremity prosthesis and the myoelectric signal in general, it was decided that the focus would be directed towards haptic feedback, and to relate that to the Hy5 hand. With the focus shifted to an aspect of prostheses without the same level of commercialisation, the source of information became research articles and papers. The first objective was to get an overview of the field.

To understand the role of feedback in prosthesis, an understanding of feedback in motor control for the unimpaired was sought. First, an overview of what is sensed by the receptors in a human hand was examined. Then, the role of said feedback in motor control was examined.

Then, in parallel , the literature study was focused on previous works on haptic feedback in upper limb prosthesis. To understand how to create something useful for the Hy5 hand, an understanding of different schools of thought and architectures was sought. Different sensors and actuators were looked into, both as parts of a whole system, and as individual components.

4.2 Previous Work

In this section, some of the previous works on haptic feedback is presented. Note that this represents only a small fraction of the studies and articles published.

4.2.1 Schoepp, K. *et. al.*

In [25], capacitive sensors are placed under a layer of nitrile on the thumb and index finger on an existing prosthesis. The forces detected by the sensors were then transferred, via a MCU embedded into the arm of the prosthesis, to specially designed tactors; small motors which pushed down on the skin, creating a linear force sensation on the skin of the prosthesis user. The assembled system was tested by one prosthesis user in a controlled environment, where the time and force required to move a small object was recorded with and without the haptic feedback engaged.

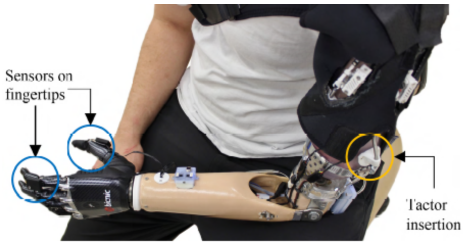

Figure 4.1: Figure of the complete system, integrated into an existing prosthesis. From [25]

4.2.2 Antfolk, C *et. al.*

In [2], a silicone bulb connected via a plastic tube to a silicone pad placed on the skin of the residual limb of several prosthesis users as well as several unimpaired subjects. Contact forces on the fingers of the prosthesis was thus transmitted to the user via air pressure, without the need for electronics or any active components. By placing the actuating bulbs on the phantom maps (2.6), the system achieved somatotopic matching, as well as modality matching, for the subject who had at least a partial phantom map.

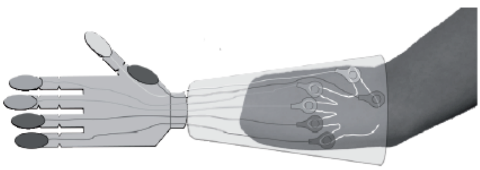

Figure 4.2: Conceptual scetch of the air mediated system from fingertips to phantom map. From [2]

4.2.3 Aboseria, M. *et. al.*

In [1], visual, discrete vibrotactile and continuous normal force feedback, is compared to determine which is most efficiently enables users to regain a stable grip when and object starts to slip. The study's duration was three days, and while it was thought that the continuous feedback of grip force would be more useful, even after three days of training the discrete vibrotactile stimulation was more efficient at preventing object slippage and crushing when regripping.

4.2.4 Barone, D. *el. al.*

In [4], a cosmetic digit, i.e finger, is designed and constructed which includes a FSR, a vibrotactile stimulator, controller and other supporting circuitry. The system is based on the Discrete Event-driven Sensory feedback Control (DESC), discussed in [12]. The vibrational motor was controlled such that it gave a short burst of stimulation whenever an object was grasped or let go. During lab trials, the digit outperformed simple cosmetic prosthesis in a virtual egg test. One digit prosthesis user was given the system to test in their daily life, and anecdotal reports stated that the system was very useful in object manipulation tasks.

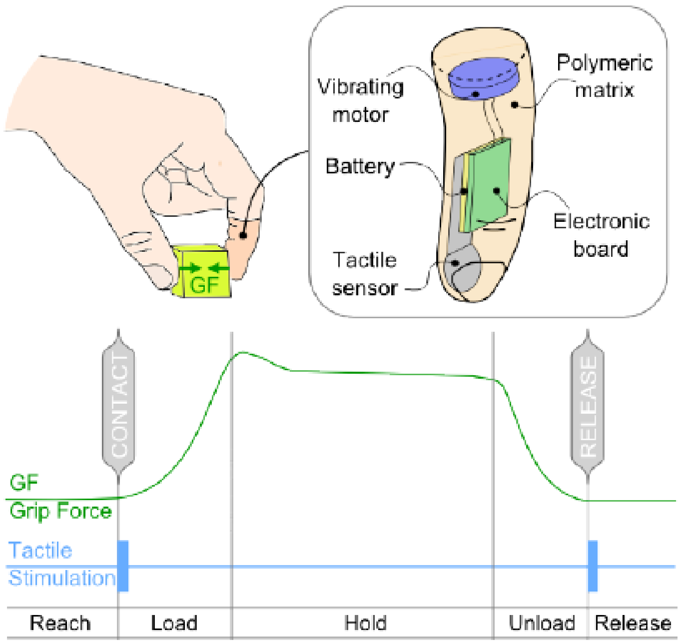

Figure 4.3: Conceptual sketch of the cosmetic digit. Underneath is a time line of the grip force (GF) and the corresponding tactile stimuli. From [4]

CHAPTER

FIVE

PROPOSED ARCHITECTURES

5.1 Sensors on Hand

A system like the one designed and tested in [25], could be implemented for the Hy5 hand, with sensors placed on the fingertips, and under a cosmetic glove. A micro-controller unit (MCU) could be housed within the socket part of the prosthesis. From the MCU actuators placed within the socket can be controlled and tuned. In addition to the control of sensors and actuators, a system with a MCU can include a wireless control interface for tuning even after the system has been installed in the prosthetic system.

The feedback provided by the actuators can be either continuous, or event driven. The events can include object slip, contract with an object, or completing the gripping part of Hy5's adaptive grip , see 3.2.

Pressure sensors could also be embedded within the hydraulic system and the readings from these could be used a the reference signal for the force feedback. Current Hy5 designs only have one high pressure zone, and thus only the average or total pressure of the digits is available for feedback, but should future designs include a separate and controllable zone for the opposing thumb, it should be possible to provide the user with information about the forces in the opposing sides of the hand without the need for exposed sensors.

5.2 Hydraulic or Pneumatic System

As in [2], a simple pneumatic coupling, can be used to give the user information about contact forces. Taking this concept further, utilising the hydraulics in the Hy5 hand to create a pressure on the skin of the prosthesis user could be possible. This would require no additional circuitry, and by only connecting the stimulating pad to the high pressure zone of the hydraulic system in a non looping way the added components would not induce any significant additional flow of hydraulic fluid. While both these variations are simple in their idea, they lack easy tuning and user adaptability other than choosing the stimulation zone.

5.3 Using EMG-signal

An alternative to using force sensors or a fluid to transmit pressures to the user is to give the user tactile information based on the strength of the EMG-signal. While this will not give the user information about the real state of the prosthesis, it will allow the user to gauge his or her signal strength and thereby adjust. While such a system til still require a MCU and actuators, the sensors are already in place as part of the existing prosthetic system.

CHAPTER

SIX

DISCUSSION AND RESULTS

6.1 Discussion of Previous Work

6.1.1 Schoepp, K. *et. al*, see 4.2.1

The system developed by Schoepp and others is of a lightweight and modular design, allowing for easy integration into an already existing prosthetic system. The sensor demonstrates the ability to function and detect changes in applied pressure, even when covered by a nitrile fingertip. While the average force applied to the object when grasping and lifting was reduced when haptic feedback was enabled, the time to complete the task increased. Schoepp argues, in line with other experiments [30], that this difference in time would be reduced given more training time with the haptic feedback, though this is a point of future research.

6.1.2 Antfolk, C *et. al*, see 4.2.2

The idea for the system developed by Antfolk *et. al* dates back to the 1930 [26]. The addition of the feedback system to an existing prosthesis adds little weight and by its passive nature puts no extra load on the battery of the system. Simple in design, and cheap to manufacture, the air pressure system could provide a one size, fits most solution to the haptic feedback problem. However, in it simplicity, the system lacks any real tuning abilities other than pad placement. Also, as demonstrated in [1], discrete vibrational pulses prevented object slip better than continuous feedback.

6.1.3 Barone, D. *et. al*, see 4.2.3

While the feedback system designed was not for a whole hand, but only a finger, it demonstrated how events, communicated through vibration, was an effective tool in motor control. The use of an FSR demonstrated that despite its lacking accuracy, it was useful in determining at least two different events, contact and release, during the lifting and holding of an object.

6.2 Discussion of Proposed Architectures

6.2.1 Sensors on Hand. See 5.1

A system with sensors placed on the fingers of the prosthetic hand will most closely resemble the natural sensor placement of the proposed architectures. [25] demonstrated that a sensor could function under a layer of protective ”skin”, which is vital for the reliability and longevity of a feedback system. For the Hy5 prosthesis, it is proposed that three sensors, on the thumb, index and middle fingers is proposed. These are the fingers which are currently able to move with some degree of independence.

Using a MCU with a communication interface to the outside will allow for personalising of the stimuli to be delivered while the system is in use by the user. The users of such a system will have a varying degree of sensory ability in the residual limb, and thus the sensitivity to different stimuli will vary.

Adding a MCU, several sensors and actuators will clearly increase the weight of the prosthesis. Weight reduction is one of the most cited needs of the users of upper limb prostheses [8]. However, so is sensory feedback, and with the right choice of components the haptic feedback system can hopefully be made lightweight enough such that what is gained can justify the added weight.

The system will draw some power in order to operate the sensors, MCU and actuators. Sourcing the power from battery already included in the system will possibly reduce the time between recharges of the prosthesis. However, as demonstrated in [25], the average grip force was lower when feedback was enabled, thus lowering the power draw of the motor and possibly resulting in a net reduction of power usage.

Adding sensors on two or more of the fingers and covering them with a cosmetic glove could be done, with little to no rework of the actual hand. The MCU, its power supply and the actuators could be housed within the socket part of the prosthesis. Placing actuators on the residual limb would require rework of the area surrounding the skin, and extra work would have to be done when fitting the prosthesis to the user, especially in the presence of a phantom limb map.

Having a pressure sensor within the hydraulics rather than on the fingertips will most likely mean losing the ability to discern much about the shape of objects, as the pressure will only build up to significant levels when the hand has closed around an object. A benefit of such a system is that the sensor no longer is exposed to whatever the hand is touching, and that there will not be a need for cables to run along the moving fingers.

For users where it is possible, actuating areas which correspond to the phantom limb map it thought to be beneficial.

6.2.2 Hydraulic or Pneumatic system. See 5.2

A pneumatic system like the one in [2] is simple, easy to manufacture and can be made cheaply. However, it requires a tube filled with air or some other pressure carrying medium to extend from the fingers to the site of stimulation. This would likely require a significant rework of the current Hy5 design and construction.

The simple system will however lack much of the ability of tuning a system based on a MCU holds. Also, the sensor less system cannot easily be monitored without the addition of a MCU and sensor array.

6.2.3 Using EMG-signal. See 5.3

This approach is fundamentally different than the two previously proposed, as the source of the feedback is not a force in or on the prosthesis, but rather EMG signal which is used to control what forces are to be generated. While this might not be as useful when using the prosthesis in day to day life, having direct feedback of the EMG signal during training could potentially help users adjust to using the prosthesis.

6.3 Choosing MCU-based system

After having review the literature and proposed and discussed a few architectures, it seems a system controlled by a MCU with sensors in the fingers and actuators on the skin is the best suited for the Hy5 hand. Such a system could inform the user of events during grasping, either directly though changing in normal force stimulation, or through a expanded version of [4], via vibrotactile stimulation. Having a combination of both normal force stimulation for force feedback as well as a vibrotactile stimulator for feedback of motor control events could enable the user to both grip with only the required force as well as prevent object slippage.

A major point of uncertainty is whether users will find the feedback useful or a hindrance when using the prosthesis. Having an added cognitive load might be enough to prompt users to abandon the haptic feedback system. Many studies of haptic feedback are also confined to a laboratory setting, and thus the effect of the added cognitive load might only be apparent in real life trials. If the cognitive load of both normal force stimulation and vibration is proven too great, reverting to only vibrotactile to communicate events is thought to be the better option. Direct nerve stimulation might be a solution to this problem, as, at least in theory, it should be possible to create the same sensations as for individuals not lacking a limb. Failing this, TMSR could be a step closer to somatotopic matching and reduced cognitive load.

The system proposed also only includes force feedback. It is unclear whether proprioception is the missing component in making haptic feedback viable.

CHAPTER

SEVEN

CONCLUSION AND FUTURE WORK

7.1 Conclusion

The system proposed is a MCU-based system with sensors placed in the three of the fingers of the Hy5 prosthesis. There are several uncertain aspects of the proposed system, including: cognitive load, ability to use force sensors to detect events and usability outside of a laboratory setting. The two most important aspects of haptic feedback in motor control seems to be the maintenance of internal forward models and the detection of transitions between states in motor control.

Prosthetic hands is a multidisciplinary field, and the success of any system requires that all parts of the system, from the hand to the fitting of the socket or the surgeon possibly performing osseointegration or TMSR, work together in a compatible way.

7.2 Future Work

Future work will include creating a prototype of the haptic feedback system. This includes hardware as well as software development. An analysis of which events is detectable and communicable to the user with the proposed sensory array and actuators must also be undertaken.

When a prototype has been created, testing the system on prosthesis users in a as realistic scenario as possible is key to determining if the system can be used and commercialised.

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