Two-channel user-feedback for hand prosthetic

A TTK4550 Project Report

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2021

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Project Assignment

Student's name: Kristine Stray

Field: Engineering Cybernetics

Title (Norwegian): To-kanals brukertilbakekobling i håndprotese

Title (English): Dual-channel user feedback in hand prosthesis

Description:
A natural hand is mechanically and neurologically integrated with the rest of the person's body. One important function of this system is that joint positions, speeds, forces and torques in the hand are communicated to the brain via the nervous system so that the person always knows what is "going on" while the hand is being used. Such feedback enables precise and delicate movements and manipulations.
In case of amputation, most such feedback paths are broken. In this project you will develop and test a system to restore feedback to the user of the aperture (i.e. the degree of opening) of the hand, and of grip force.

This term project is a precursor to a coming MSc thesis project, and its scope should therefore be set according to this larger perspective, which would typically include parts of the following:

- Literature study regarding the possibilities and limitations of haptic feedback in prosthetics,
- design and implementation (or improvement, in case of re-used components) of a feedback device,
- definition of a suitable and realistic assessment protocol,
- application to the Regional Ethics Committee,
- practical assessment of the chosen feedback device.

Deciding/limiting the scope of the term project is part of the assignment itself.

The assignment is based on previous student projects, and reuse of previous system components are encouraged to the extent that is contributes to progress and to the quality of the results.

Co-supervisor(s): Bjørn O. Bakka, Hy5

Trondheim, 16. September 2021

Øyvind Stavdahl
Supervisor

Preface

I want to thank my supervisor, Øyvind Stavdahl, for all the enlightening discussions. You are an extremely knowledgeable man, and your optimistic views continue to inspire me beyond the work of this thesis.

A special thanks to Bjørn Olav Bakka at Hy5, without whom there would not be a project for me to work on. Also, thank you for providing valuable insight into the world of prosthetics. It is most appreciated.

I want to thank my family and friends for their not-asked-for but much-needed support. Thank you, Mom, for asking all the stupid questions that I did not dare ask myself. Thank you to my dear partner, Håvard, both for supporting me and for challenging me. You always know what I need and when I need it, even though I don't.

The following is my take on the possibilities and limitations of haptic feedback devices. This project is my humble attempt at making even the tiniest contribution toward better haptic feedback devices for prosthesis users.

Abstract

This project explores the possibilities and limitations of haptic feedback in prosthetic devices. Few have studied the effects of delivering feedback for both grip force and hand aperture through the same feedback device, but the need for dual-channel feedback has proved evident. On the basis of a literature study focused on feedback methods for providing grip force and hand aperture through either vibrotactile or mechanotactile feedback, a design for a haptic feedback device is presented. Previous work has shown that modality-matched feedback is superior to sensory substitution, as modality-matched feedback is perceived as more intuitive. Vibrotactile feedback is usually regarded as a method for providing sensory substitution, whereas mechanotactile feedback is more easily matched to the modalities on which it seeks to give feedback. Therefore, the proposed design entails a mechanotactile feedback device that can provide squeeze and stretch for grip force and hand aperture, respectively. Future work includes implementing and testing the proposed feedback device in order to evaluate whether it is effective in providing haptic feedback to the user.

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Chapter 1

Introduction

1.1 Background and motivation

Take a short moment to imagine how it feels to shake someone's hand. The sense of touch contributes to form a mental image of the shape and size of the other person's hand. In a sense, humans can "see" with their hands without looking at what they are touching. Now imagine the situation without receiving any form of sensory feedback from your own hand. Did you squeeze to hard? Did you shake their hand at all? This essentially describes how it would feel (or not feel) for a person with a prosthetic hand. In the case of amputation, the sensory feedback from the hand is lost, not to mention the functionality of the hand itself. Though the research on artificial sensory feedback has been ongoing since the 1970s, no commercially available prosthesis provides artificial feedback that has been demonstrated effective performance in clinical trials.[1]

Despite some of the functionality of the hand being restored through a prosthetic device, the embodiment – the sense of self-attribution – of the prosthetic device is generally low.[2] Through an epidemiologic overview of the priorities of individuals with upper-limb loss, Atkins *et al.*[3] recognized poor manipulability of prosthetic devices due to the lack of sensory feedback as a leading cause of prosthesis abandonment. More recent works, including the review performed by Cordella *et al.*[4], point to similar reasons for why lack of feedback promotes prosthesis abandonment, including poor control and autonomy in daily life tasks. In addition, without haptic feedback, the amputee must often rely on visual aid when controlling a prosthetic device, resulting in high cognitive load.[5]

A feedback device can provide little value on its own, unless recognized as part of a closed-loop prosthetic system. Additionally, the device must provide information beyond what is already available from the intrinsics of the prosthetic device. The literature on this field recognizes the need for intuitive sensory feedback, and suggests that grip force and hand aperture, among others, should be provided to promote prosthesis embodiment.[1, 2, 4, 6]

A challenge with artificial feedback is that it is often unintuitive. Sensory substitution through vibrotactile feedback has proved useful in certain grasping tasks, but its usage is limited for providing hand aperture feedback.[7–9] Sensory substitution provides feedback through a different feedback channel – the medium that delivers feedback – than what is normally used, which means that the user must learn to associate the feedback with the sensory information it is trying to provide. A more intuitive alternative is modality matching, as modality-matched feedback mimics the sensory stimuli naturally produced in the skin. Several research groups propose that skin stretch is a suitable feedback method for hand aperture feedback, as skin stretch is thought to activate the same type of mechanoreceptors that would otherwise be stimulated when opening and closing the hand.[10–12]

Providing artificial sensory feedback is a challenging task, even when the feedback is modality-matched. This thesis attempts to contribute to the research on sensory feedback in the hope that artificial feedback one day can improve the quality of life of those less fortunate.

1.2 Interpretation of project task and scope

The project description states that this project will involve the development and testing of a feedback system that gives the user information about hand aperture and grip force. The *project* is interpreted as consisting of both the term project and the future MSc thesis project. A decision has been made to include the following parts in the term project:

- Familiarize with and present necessary theory related to haptic feedback.
- Literature study regarding the possibilities and limitations of haptic feedback in prosthetics, with special attention to systems that focus on hand aperture and grip force.
- Come up with a design proposal for a feedback device – either new or an improvement of an existing device.

The first point is added to emphasize that the author of this thesis had no previous knowledge related to the field of haptic feedback. This is further explained in Section 1.3.

As stated above, special attention should be paid to systems that focus on hand aperture and grip force. This is an attempt to limit and focus the literature study, which can help ensure the quality of this thesis. Based on the literature study, a justified choice for the design of a feedback device should be made. A justified choice should include discussing the design choices in light of the presented theory and literature.

The remaining parts from the project description are considered part of the MSc thesis project. This includes implementing the proposed feedback device, defining an assessment protocol, applying to REC (if applicable to the assessment protocol), and practically assessing the proposed feedback device according to the chosen assessment protocol. Choice of materials to realize the proposed design is reserved for the MSc project, as this is considered part of the implementation process.

1.3 Contributions

Prior to the start of the term project, the author of this thesis had no knowledge within the field of haptic feedback for prosthetic devices, and her knowledge of human anatomy and physiology was limited. Therefore, a relatively large amount of time has been spent exploring and understanding the theory. Additionally, reading up on previous work required a substantial amount of time and effort, as the author was learning the necessary theory alongside conducting the literature study. This limited the time available for developing the design of the proposed feedback device, and the design is therefore only presented conceptually.

The supervisor, Øyvind Stavdahl, has provided guidance and feedback throughout the term, while the responsibility of making decisions and choices remained with the author.

1.4 Outline

Following this introduction is Chapter 2, which presents the theory. The theory is divided into two sections; the first section introduces concepts related to anatomy and physiology of the human body. This section lays the foundation for what is presented in the second section – feedback for prosthetic systems. Next, Chapter 3 presents the most relevant articles of the literature study and explains the method in which the author proceeded to collect and review the work presented in this chapter. Based on the literature, design choices are evaluated and presented in Chapter 4, together with a design proposal for a feedback device. The design proposal is discussed in Chapter 5. Finally, Chapter 6 presents concluding remarks and proposes what should be done in terms of future work.

Chapter 2

Theory

2.1 Anatomy and physiology of the human body

"Anatomy refers to the internal and external structures of the body and their physical relationships, while physiology refers to the study of the functions of those structures." [13, p. 74]

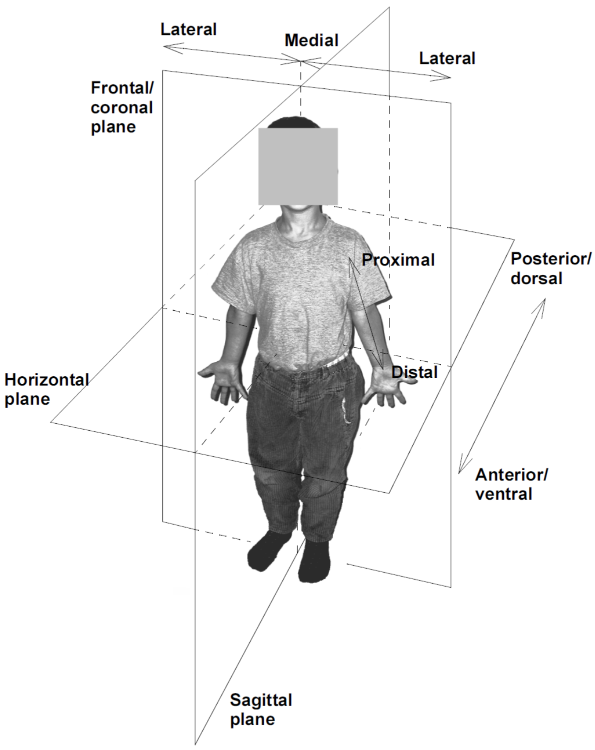


Figure 2.1: The anatomical planes and directional terms. Adapted from [14].

In order to refer to and describe the human body, it is handy to define some anatomical planes and terms that are used to describe the position of a body part.

As reference, the *anatomical position* is used. When standing in the anatomical position, the body is facing forward, the arms are hanging to the sides with palms facing forward. This position, labeled with the anatomical planes and directional terms, is shown in Figure 2.1. The figure shows the ventral (or anterior) side of the body. The directions *proximal, distal, medial, lateral, ventral* and *dorsal* are used to describe the relative position of a body part. Often, the attached end of a limb is used as a reference point to define whether a body part is proximal or distal to the end of the limb. For instance, the elbow is proximal to the shoulder since it is closer to the shoulder, while the hand is distal to the shoulder, since it is further away from the shoulder. If a body part is located close to the midline of the body, it is said to be medial. On the other hand, a body part far from the midline is said to be lateral. Finally, ventral implies that something is in front of or on the front side of the body, while dorsal means behind the body. [13, p. 74-75] Some additional directional terms are also used, but only those relevant for this thesis are included here. Proximal and distal are the two most important directional terms for this thesis.

2.1.1 The nervous system

The nervous system can be divided into the Central Nervous System (CNS) and the Peripheral Nervous System (PNS). The CNS consists of all nervous tissue that is enclosed by bone – i.e. the brain and the spinal cord. The PNS entails "all the rest" – i.e. the nervous tissue that is not encased by bone. [13, p. 107] Nerve cells that carry information from the periphery *toward* the CNS are called afferent neurons. Nerve cells that carry information *away* from the CNS – or away from the circuit in question – are called efferent neurons. [15, p. 10] Afferent neurons play an important role in the somatosensory system, which is explained in Section 2.1.3.

Electrical signals of neurons

Generally, all cells of the human body have electrical potentials across their membranes. Some cells, such as nerve cells (also called neurons), are able to generate electrochemical impulses at their membranes. When at rest, the neuron has a negative voltage potential accross its cell membrane. This membrane potential comes from a difference in concentration of certain ions – sodium and potassium ions – inside and outside the cell membrane.[16, p. 57]

Neurons transmit information throughout the nervous system by what is called **action potentials**. An action potential is triggered when the membrane potential is increased (depolarized) and reaches a certain threshold potential. During the depolarization stage, the membrane's permeability changes to allow sodium ions into the cell. Being positively charged, the sodium ions increases the potential across the cell membrane. The action potential propagates along the nerve fiber's axon until it reaches the end, which is connected to another nerve cell, thus triggering another action potential.[15, p. 33-35][16, p. 60-61]

2.1.2 The musculoskeletal system

The musculoskeletal system consists of the skeletal system and the muscular system. Very briefly, the skeletal system is made up of rigid bones that form the major supporting and protecting elements of the body. The bones are attached to each other at three different types of joints, namely fibrous, cartilaginous and synovial joints. Bones connected by fibrous joints are bound tightly and are relatively immovable, like the joints in the skull. Cartilaginous joints, like the joints that attach the ribs to the spine, allow some movement. The knee and elbow are examples of synovial joints, which consist of cavities that are filled with fluid, as well as connective tissue that holds the bones together. [13, p. 111-113]

Detailed knowledge about the skeletal system is not required for understanding the concepts presented in this thesis. However, both the metacarpophalangeal joint and the proximal interphalangeal joint, shown in Figure 2.2, are mentioned in the literature. The metacarpophalangeal joints are the synovial joints where the bones of the fingers – the phalanges – meet the bones of the hand – the metacarpals.[1] The interphalangeal joints are the synovial joints connecting the phalanges. The one closest to the hand is called the proximal interphalangeal joint.[13, p. 111-113]

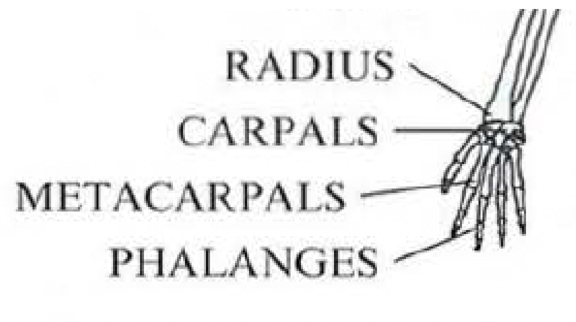


Figure 2.2: Illustration of the major bones of the human hand. Adapted from [13].

The muscular system consists of three types of muscle tissue; skeletal, cardiac and smooth muscle tissue. The heart is the only place where one can find cardiac muscle tissue, while smooth muscle encapsulates tissue in almost all organs. Skeletal muscle, which consists of skeletal muscle tissue and connective tissue, as well as blood vessels and nervous tissue, is attached to bone, skin or other muscle tissue. Skeletal muscle is what moves the bones and joints of the body, as well as the skin of the face.[13, p. 113-116] Of particular importance to hand prosthesis control are the flexor and extensor muscles of the forearm. More on this in Section 2.2.1.

[1]In other words, the knuckles.

2.1.3 The somatosensory system

There are three sensory systems in the human body; the somatosensory, the visual and the vestibular system.[17, p. 60-61] The focus of this thesis will be on the somatosensory system, which includes the somatic sensations of touch, pressure, vibration, limb position (also known as proprioception), pain and temperature, among others. Each type of sensation is called a **modality**.[16, p. 559] These sensations are detected by different types of receptors in the skin, muscles, tendons and joints, and transmitted to the CNS where the information is processed.[15, p. 181]

The mechanism of detecting and transmitting somatic sensations is called sensory transduction, which involves that energy from a stimulus is converted into an electrical signal. When a stimulus, for example touch, excites the receptor, the receptor's membrane permeability is altered. This opens ion channels that allow ions to diffuse through the membrane, generating a depolarization of the membrane potential – known as a **receptor potential**. The depolarization triggers an action potential on the afferent nerve of the receptor, and the action potential propagates along the axon until it reaches its target in the CNS.[15, p. 181-183] This is illustrated in Figure 2.3.

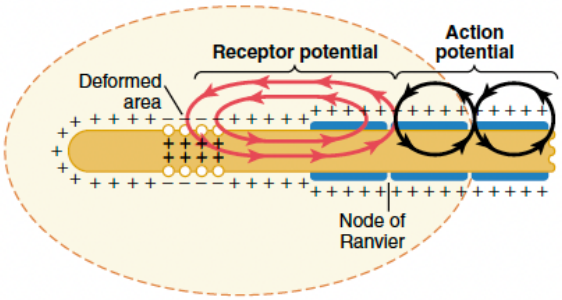


Figure 2.3: Excitation of a sensory afferent neuron produced by a receptor potential. From [16].

There are different types of receptors that react to different types of stimuli. One type of receptor can be almost nonresponsive to a certain stimuli, while being highly sensitive to another.[16, p. 559] Receptors that detect and transmit sensory stimuli from touch are called mechanoreceptors. The afferent terminals of the mechanoreceptors are often sheathed by specialized receptor cells, and the role of these cells is to attune the afferent fiber to receive sensory stimuli.[15, p. 182]

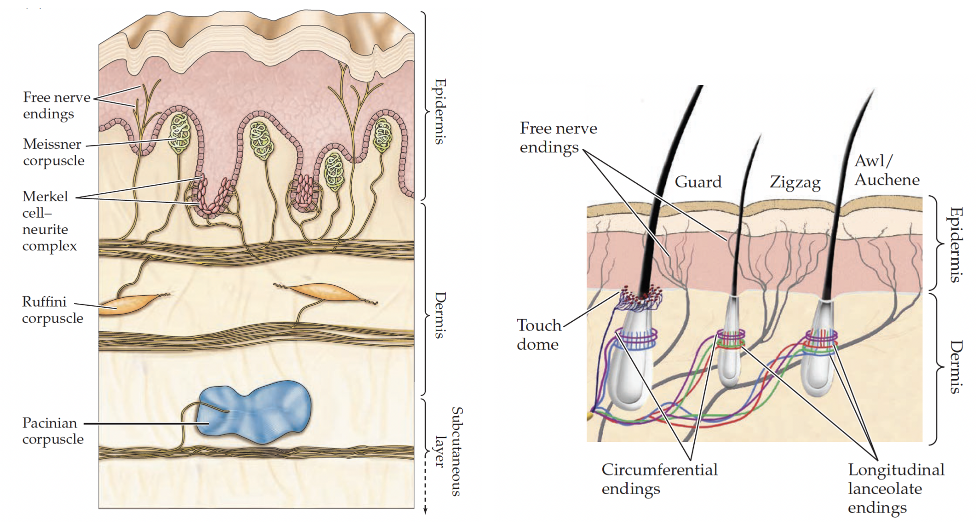
Mechanoreceptors for tactile information

The skin contains different types of mechanoreceptors, often called cutaneous[2] receptors. They differ in structure and function and are located in different layers

[2]"Cutaneous" means relating to the skin.

of the skin, as shown in Figure 2.4. Different types of cutaneous receptors produce different *tactile* sensations when they, or the areas surrounding them, are deformed.[17, p. 66]

The skin of the palms and fingertips, as well as the lips and soles of the feet, consists of glabrous skin, which is smooth and hairless. When touching an object, the different receptors in the skin of the palms and fingertips contribute to the creation of a high-definition neural image of the object[3]. *Haptics* is the interpretation of the patterns that are produced by the stimuli activated by the different mechanoreceptors in the glabrous skin when one touches an object. In hairy skin, tactile stimuli are detected and transmitted by mechanoreceptors connected to different types of hair follicles, as illustrated in Figure 2.4b.[15, p. 185]



(a) Glabrous skin

(b) Hairy skin

Figure 2.4: The skin contains different types of mechanoreceptors located at different layers. Adapted from [15].

Here follows a brief explanation of the different cutaneous mechanoreceptors and the kinds of tactile sensations they produce.

Merkel disks: Merkel disks are located in the epidermal ridges, which are the prominent ridges where the epidermis extends into the dermis, as shown in Figure 2.4a. Being slowly adapting receptors, Merkel disks respond to slow movements accross the skin's surface. The fingertips are especially enriched with Merkel disks, and generally they make up about 25% of the mechanoreceptors in the inside of the hand. Additionally, Merkel disks are sensitive to points and edges, meaning they can provide information about shape and texture.[15, p. 186]

Meissner's corpuscles: Meissner's corpucles are located in the superficial layer of the skin. Due to their close proximity to the skin's surface, Meissner's corpuscles

[3]For instance, manipulating an object with the hand can often provide enough information to identify the object without the use of visual aid. This is called stereognosis.[15, p. 185]

are highly sensitive to skin deformation. Being rapidly adapting fibers, they respond easily to light touch. It is believed that Meissner's corpuscles are responsible for slip detection when holding an object because of their ability to detect low-frequency vibrations. These vibrations are in the range $3-40$Hz and occur when for example moving one's hand over a textured surface.[15, p. 186]

Pacinian corpuscles: As shown in Figure 2.4a, the Pacinian corpuscles are located deep in the dermis or in the subcutaneous layer. The Pacinian corpuscles are stimulated by high-frequency ($250-350$Hz) disturbances or compressions of the tissue. Because of this they play a key role in detecting vibrations and other rapid mechanical changes to the tissue.[15, p. 187] [16, p. 572].

Ruffini corpuscles: Little is known about Ruffini corpuscles, except that they are slowly adapting afferents that are particularly sensitive to cutaneous stretch produced by movements in the digits or limbs.[15, p. 187]

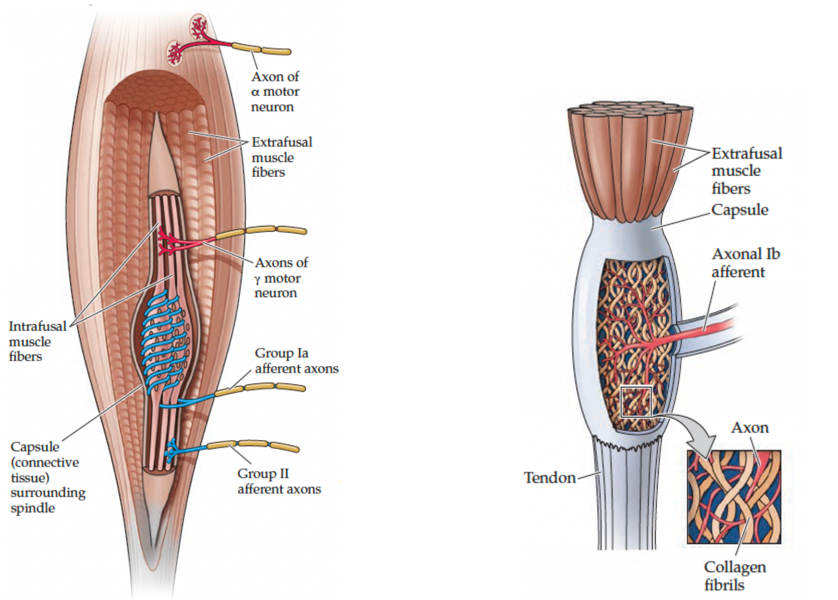
Free nerve endings: As mentioned, mechanoreceptors are encapsulated by specialized receptor cells that help with the reception of somatic stimuli. Free nerve endings are not encapsulated by these specialized receptor cells. Because of this, they have a higher threshold for generating action potentials, which means that they are less sensitive to sensory stimulation. On the other hand, free nerve endings respond readily to painful sensations. Free nerve endings that activate the sensation of pain are called nociceptors.[15, p. 182, 184]

Mechanoreceptors for proprioceptive information

Recall that proprioception is the ability to sense the position of limbs and other body parts in space. This ability is essential to the performance of complex movements. Proprioceptive information is mainly provided by muscle spindles and Golgi tendon organs. These mechanoreceptors provide information about mechanical forces that arise from the musculoskeletal system when, for instance, a limb is moved or experiences tension.[15, p. 188]

Muscle spindles, illustrated in Figure 2.5a, are located in skeletal muscle and consists of *intrafusal* muscle fibers. The intrafusal fibers are distributed among *extrafusal* muscle fibers. The extrafusal fibers of skeletal muscle are responsible for force production, which allows the movement of limbs. Two types of sensory afferent neurons, type Ia and type II, are connected to the intrafusal fibers. Primary endings, which are of the type Ia afferent neurons, are coiled around the intrafusal fiber creating a spindle. When the muscle is stretched, action potentials are triggered on these afferent neurons, thus informing the CNS about how much the muscle is stretched. Primary endings respond rapidly to changes in muscle length and transmit information about limb dynamics. Secondary endings, those of type II afferent neurons, are attached to the end of the intrafusal fiber and provide information about static limb positions. This is because secondary endings produce sustained responses to constant muscle lengths.[15, p. 188]

While muscle spindles detect changes in muscle length, Golgi tendon organs detect changes in muscle *tension*. The Golgi tendon organs consist of type Ib af-



(a) Muscle spindle

(b) Golgi tendon organ

Figure 2.5: Proprioceptors in the musculoskeletal system provide information about limb position. Adapted from [15].

ferents, and as illustrated in Figure 2.5b, these fibers are distributed among the collagen fibers of the tendons connected to the muscle. When tension is put on the muscle, the tendons are stretched, which triggers an action potential on the Ib afferents. In this way, the central nervous system is provided with instant information about the tension and strain on the muscles. If very large tension is put on the muscle and tendons, the Golgi tendon organs will inhibit the motor neurons of the muscle, acting as a negative feedback mechanism and forcing the muscle to relax. This is to avoid muscle overload and injury.[15, p. 189][16, p. 661]

Receptive field

Another property of cutaneous receptors is their receptive field, which is "the area of the skin surface over which stimulation results in a significant change in the rate of action potentials". Put simply, it affects the spatial accuracy with which tactile stimuli can be sensed. The receptive field is closely linked to the branching structure at the end of the afferent nerve. Smaller and finer branching gives a smaller receptive field, which means better spatial accuracy.[15, p. 183-184]

The two-point discrimination threshold determines the minimum distance that is required to distinctly perceive two stimuli that are applied to the same spatial region simultaneously. Figure 2.6 shows the differences in two-point discrimination threshold across the surface of the human body. Because the two-point discrimination threshold of the fingers, toes and face is much lower than in the arms, legs

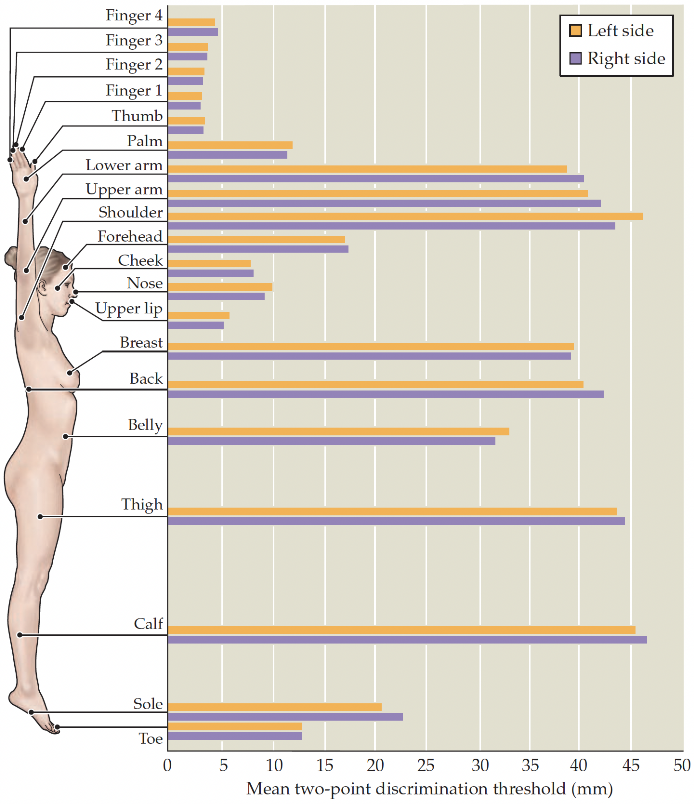


Figure 2.6: Differences in the two-point discrimination threshold accross the surface of the human body. Adapted from [15].

and torso, the spatial accuracy of the fingers, toes and face is much higher.[15, p. 184]

The distribution of cutaneous receptors throughout the body varies, with the greatest number of receptors found in glabrous skin, such as the lips, fingers, palms of the hand and soles of the feet. The higher concentration of receptors results in greater tactile sensitivity in these regions of the body. In contrast, the number of cutaneous receptors in the arms, trunk and legs is considerably lower. The different levels of tactile sensitivity associated with different body parts also influence the type of motor control possible. Those body parts with the highest level of tactile sensitivity are involved in the performance of movements requiring fine motor control[4], whereas other body parts are involved in more gross types of motor control.[17, p. 67]

[4] An interesting fact is that Pacinian corpuscles are found in their highest densities in the soles of the feet where they are believed to play an important role in different aspects of posture and locomotion.[17, p. 67]

Sensory adaption

A sensory receptor adapts to a stimulus by reducing its level of firing soon after the stimulus is applied. How quickly this happens depends on the type of receptor. Though exposed to the same type of stimulus, rapidly adapting receptors and slowly adapting receptors will have different firing patterns as a result of different receptor potentials. This is illustrated in Figure 2.7. Receptors that transmit sensations of vibrations adapt rapidly, whereas certain proprioceptors adapt relatively slowly.[17, p. 61-62]

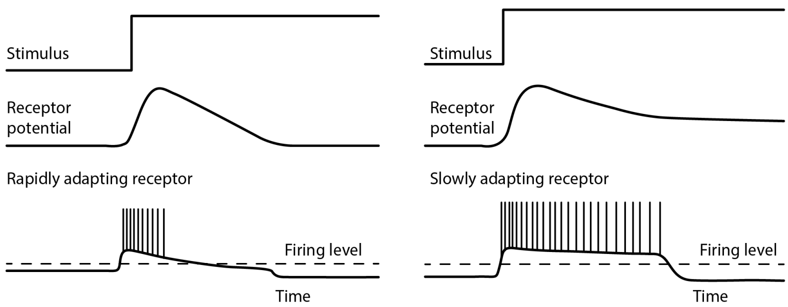


Figure 2.7: Illustrating the different sensory adaption rates of rapidly and slowly adapting receptors, indicated by the different receptor potentials and firing patterns. Adapted from [17].

The differences in adaption rates are essential for being able to distinguish between different sensations, like a tap on the shoulder or stretching the skin. Merkel disks and Ruffini corpuscles are examples of slowly adapting receptors.[17, p. 66]

2.2 Closed-loop prosthetic systems

A brief introduction to closed-loop prosthetic systems is given here. Being its own field of research, control of prosthetic devices is not covered in great detail. Emphasis is put on artificial sensory feedback, and only the topics necessary to understand the workings of simple closed-loop prosthetic systems are presented here. For simplicity's sake, only electrically powered prosthetic devices are regarded, although it should be mentioned that other types – body-powered prostheses – exist.

2.2.1 Prosthesis control and pathways for feedback

After a transradial (below the elbow) amputation, the lost motor functions can, to a certain degree, be restored by using an electrically powered hand prosthesis. Typically, electrically powered hand prostheses are controlled by electromyographic (EMG) signals and are then usually referred to as myoelectric prostheses.[1, p. 127] EMG electrodes measure the electrical activity produced when a muscle is contracted.[5] Myoelectric prostheses are controlled by "commands" translated from the electrical activity of the user's muscles. The muscle activity is measured by surface EMG (sEMG) electrodes targeting the flexor and extensor muscles of the forearm. These are the muscles that, before amputation, were used to move the hand. In myoelectric hand prostheses, the activation of these muscles is mapped to analogous functions, such as opening and closing the hand, in the prosthetic device, making the control intuitive.[1, p. 148]

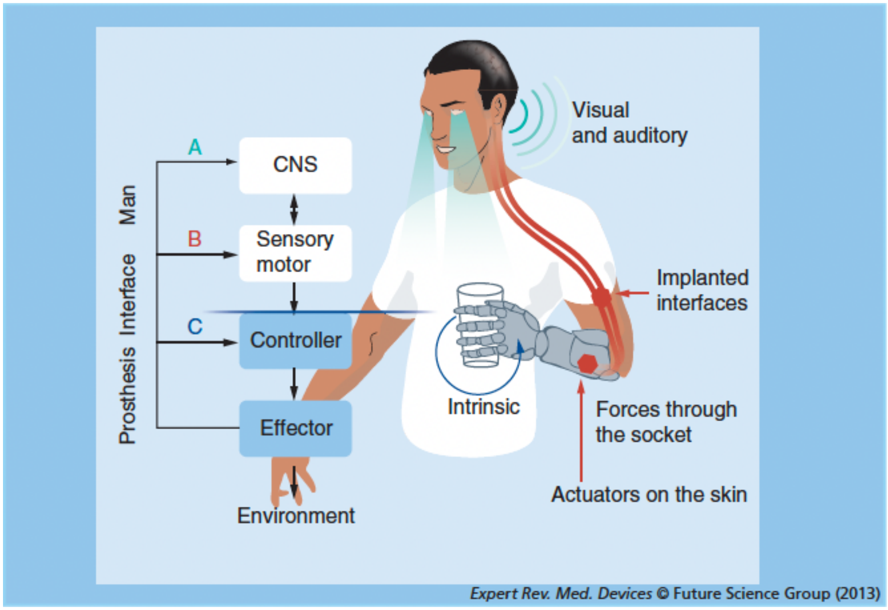


Figure 2.8: Diagram of a human-prosthesis system, including its information pathways. From [5].

Another function that is lost after amputation is the transduction of sensory feedback. Though the transduction of sensory information cannot be restored completely, there are ways to provide artificial sensory feedback. Artificial feedback can be delivered either invasively or non-invasively. Invasive feedback involves directly connecting to and stimulating nerves in the nervous system, and requires surgery. Non-invasive methods provide sensory stimuli through actuators that for example impose force or vibration on the skin, which is felt as tactile stimuli.[5]

Figure 2.8 shows a closed-loop prosthetic system and illustrates the different pathways that can be used for providing sensory information to prosthesis users.

Pathway **A** refers to the direct link between the sensory information and the CNS, like visual or auditory feedback. Pathway **B** consists of the sensory signals transmitted either directly, through implanted interfaces, or indirectly, via actuators on the skin. Note that the prosthetic socket can produce incidental forces or vibrations to the skin of the residual limb. This will also send sensory signals to the CNS, and is therefore a part of pathway **B**. Finally, pathway **C** includes the inner feedback loop of the prosthetic device's control system. For example, a prosthetic hand can be equipped with force-sensing resistors (FSRs), and through feedback of the inner loop, the prosthetic hand can automatically adjust the grip force or hand aperture and thus avoid breaking an object that is being gripped. However, if the user of the prosthetic device is to regulate grip force or hand aperture based on sensory stimuli, the loop must be closed at pathway **B**. There is nothing in the way of having both pathway **B** and **C** closed, and this would probably be beneficial as pathway **C** replicates the adjustment of, for instance, grip force that would otherwise occur subconsciously. Pathway **A** is usually closed by default.[5]

Whether the feedback is invasive or non-invasive, there are two main methods for providing sensory feedback – sensory substitution and modality matching.

2.2.2 Sensory substitution

Most feedback systems for myoelectric prostheses provide feedback through sensory substitution. This means that the sensory information, for example touch, is provided to the body either through a different sensory channel than what is normally used or through the same channel but as a different modality, for example vibrations. If sensory information from touch is to be substituted with, for example, vibrations to convey information about the prosthetic hand's grip force, the user of the prosthetic system must first relearn how to interpret the sensory information.[5]

2.2.3 Modality matching

If the sensory information provided by the feedback system is perceived as the same modality as the sensory input – for example force on the prosthesis' digits is felt as force on the skin – the feedback is said to be modality matched. Producing pure modality matched feedback is a challenge, but the feedback method can mimic the sensation of the type of information it is trying to convey. Though the stimuli is perceived at a different body part (usually the skin of the forearm or upper arm), this type of feedback is considered more intuitive than sensory substitution, since the stimuli matches the natural sensory input that would otherwise occur in the hand.[5]

2.2.4 Non-invasive methods for haptic feedback

This section in inspired by Chapter 15 *Prosthetic Feedback Systems* from the book *Bionic Limb Reconstruction* by Aszmann and Farina[1].

Electrotactile feedback

With electrotactile feedback, surface elctrodes placed on the skin transmit electrical pulses that activate cutaneous afferents. In this way, the low-amplitude pulses create a tactile sensation often perceived as vibrations or tingling. If the frequency is high enough, it can also be perceived as constant pressure at the surface of the skin. The intensity of the sensation is determined by the charge of the stimuli, since this affects the number of activated sensory afferents. Nociceptive afferent fibers are activated when the amount of charge passes a certain limit, kown as the pain threshold.[1, p. 149]

One advantage with electrotactile feedback is the fast response to control inputs. Another advantage is the possibility of producing a variety of stimulation patterns since the stimulation parameters can be adjusted independently and simultaneously. However, electrotactile stimulaiton can be uncomfortable or even painful if the parameters are set too high. Also, electrotactile feedback is often associated with electrical shock and can therefore unnerve some users. Another downside is that "electrotactile stimulation is inherently unselective", meaning that targeting specific mechanoreceptors and afferents is not possible.[1, p. 149-150]

Vibrotactile feedback

Another feedback method is vibrotactile feedback, in which vibrations are used to stimulate the activation of mechanoreceptors in the skin. Different types of actuators and tactors that can produce vibrations exist. Being one of the simplest types of vibration motors, the coin motor only has one control input, which is motor speed. The coin motor consists of an eccentric rotating mass (ERM) and produces vibrations by rotating this mass about its motor shaft. Though the coin motor only has one control input, the need for adjusting both intensity and frequency simultaneously can be addressed by integrating several coin motors into an array. The array of coin motors can then be used to produce more complex stimulation patterns.[1, p. 150]

Another, more flexible, type of vibration motor is the voice-coil actuator. The actuator consists of a solenoid and a mass, which is connected to the base of the motor. By attracting and retracting the mass, the motor produces vibrations, and by adjusting the amplitude and frequency of a sinusoidal input signal, both the intensity and frequency of vibrations can be adjusted. However, being a mass-damper system, there is often a trade-off between intensity and frequency due to the resonance properties of the system. Voice-coil motors are also noisy, which in a feedback system to be used by an amputee with a prosthetic device can come across as interruptive or attract unwanted attention.[1, p. 150-151]

There are several advantages to vibrotactile feedback. First, the sensation of vibrotactile stimuli is considered comfortable and does not pose a risk of producing pain, like there is with electrotactile feedback. Additionally, vibrotactile feedback devices are both affordable and easy to apply because they usually consist of small, low-energy vibration motors available off the shelf. There is one drawback, however. Many vibration motors produce their vibrations through rotating a mass, and bringing the mass up to speed causes a delay in the stimulation delivered to the skin.[1, p. 151]

Mechanotactile feedback

The term “mechanotactile feedback” can be misleading in that vibrotactile feedback is also mechanical, and both methods stimulate mechanoreceptors in the skin. The difference lies in how the mechanoreceptors are stimulated. Mechanotactile feedback is usually delivered through forces and torques with low amplitudes, whereas vibrotactile feedback usually includes both higher amplitudes and higher frequencies. Mechanotactile feedback can, for example, be delivered by linear actuators pushing into the skin or by rotational actuators applying torque or skin stretch. A third example is pneumatic cuffs, which can deliver feedback by squeezing the arm.[1, p. 151-152]

According to Aszmann and Farina, the “biggest advantage of mechanotactile feedback devices is that they can deliver modality matched feedback”. For instance, by applying force or pressure to the skin, a prosthesis user can receive information about the prosthetic device’s grip force. Compared to vibrations or the tingling sensations from electrotactile devices, mechanotactile feedback is considered more intuitive since it is modality matched. That being said, mechanotactile feedback devices tend to be larger and more complex than those used for vibrotactile or electrotactile feedback.[1, p. 152]

Chapter 3

Literature study

3.1 Method

A literature study focused on methods for providing feedback about grip force and hand aperture has been conducted. Only non-invasive methods are considered here. To keep the literature study focused, and to allow for a more in-depth review of each article, only a selection of the articles studied are presented here.

3.2 Previous work

This section is based on the review of non-invasive sensory feedback methods performed by Stephens-Fripp *et al.* [6]. For the sake of simplicity, this chapter follows a similar setup and presents the material based on the type of feedback it explores. Some additional material is also offered to examine even more alternatives.

Compared to electrotactile feedback, users often prefer the sensation produced by vibrotactile feedback, and Stephens-Fripp *et al.* therefore argues that vibrotactile feedback can be beneficial over electrotactile feedback. Additionally, to limit the scope of this thesis and allow for more depth on each feedback method, only methods incorporating vibrotactile or mechanotactile feedback are studied. Both methods have shown promising results in providing feedback about hand aperture and grip force.

Some would probably argue that vibrotactile feedback is a type of mechanotactile feedback since they both stimulate mechanoreceptors in the skin, and vibrations are essentially mechanical in nature. However, a substantial amount of research has been published on vibrotactile feedback alone. With some exceptions, the literature seems to regard vibrotactile and mechanotactile feedback as two different types of feedback. For these reasons, this thesis will make the same distinction.

In order to limit the scope of the literature study, only non-invasive methods involving vibrotactile or mechanotactile feedback for either hand aperture or grip force (or both) are reviewed. In addition, the literature study is limited to regard upper limb myoelectric prostheses only, as it is with myoelectric prostheses that the need for haptic feedback seems to be most evident due to the cognitive load imposed on amputees.[4]

In the following sections, the term “statistical significance” is used to evaluate whether it is sufficiently unlikely that the observations from a given experiment are results of pure chance. This term is relative to each paper presented below, as some use a p-value of 0.05 while others use a p-value of 0.01, but all use the term “statstically significant” about their results. Nevertheless, there is always the possibility of the results being random. In any case, when the term “statistically significant” is used in this thesis, it referes to a p-value that is no larger than 0.05.

3.2.1 Vibrotactile feedback

Development and Real World Use of a Vibratory Haptic Feedback System for Upper-Limb Prosthetic Users[7]

As demonstrated by Rosenbaum-Chou *et al.*, vibrotactile feedback can be used to improve the recognition of grip force. The authors integrated a portable vibratory haptic feedback system into a prosthesis to test the usefulness of vibrotactile feedback when gripping objects during daily life. Six subjects with transradial amputation participated in the study. This included using the prosthesis with the integrated feedback system at home. The feedback system distinguished between three force levels – low, medium and high – and each force level was represented by different pulse frequencies and intensities. The grip force was measured by a wireless force sensor mounted on the prosthetic thumb. The sensor’s differential voltage output was used to determine the vibration characteristics corresponding to each force level. The feedback system is shown in Figure 3.1. In order to avoid desensitization, the tactors providing vibratory feedback were only activated for a few seconds for each force level.

The results of the study showed that for light and medium grip forces, the vibratory feedback improved accuracy by a statistically significant amount. In contrast, the vibratory feedback did not improve accuracy by a statistically significant amount for high grip forces.

Vibrotactile Grasping Force and Hand Aperture Feedback for Myoelectric Forearm Prosthesis Users[8]

Witteveen *et al.* recognize the need for feedback on both grip force and hand aperture when handling various objects using an upper limb hand prosthesis. Their objective is to investigate the performance of subjects with upper limb loss when partaking in object grasping tasks while receiving vibrotactile feedback on both hand aperture and grip force.

Two configurations, amplitude-modulation and position-modulation, for providing vibrotactile stimulation were examined, but only position-modulation was applied to both grip force feedback and hand aperture feedback. Providing position-

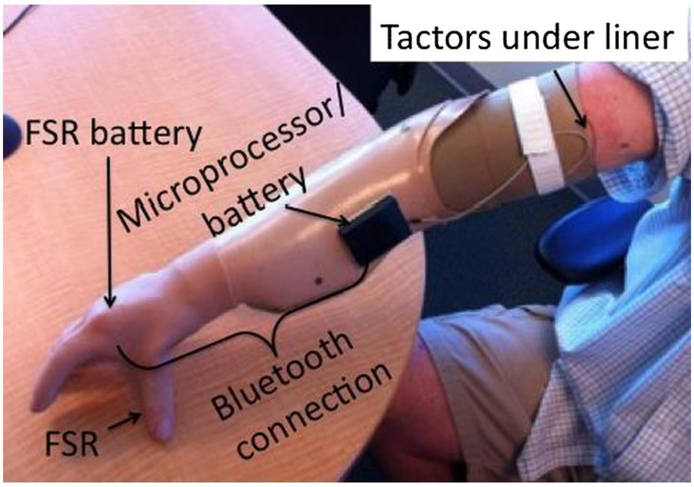


Figure 3.1: Portable vibratory haptic feedback system for testing grip force accuracy during daily use. From [7].

modulated vibrotactile stimulation was achieved using an array of eight coin motors. Each coin motor was kept at a constant voltage of 2.5V. The array was placed slightly distal to the elbow, and the coin motors were equally distributed around the arm. When providing grip force feedback, the activation of a particular coin motor was related to one of eight discrete force levels applied by the subject during a virtual grasping task.

Similarly, activating a coin motor represented one of eight possible discrete hand aperture levels when providing hand aperture feedback. The hand aperture levels ranged from fully open to fully closed. Another orientation of the array was explored in relation to hand aperture feedback. In this case, the coin motors were placed longitudinally on the dorsal side of the forearm. Activation of the most distal coin motor was related to a fully closed hand, while that of the most proximal coin motor signaled a fully opened hand.

In order to evaluate the feedback methods, the subjects performed virtual grasping tasks. A virtual representation of a hand holding various objects was used for the grip force experiments. Similarly, the hand aperture experiments showcased a virtual hand grasping objects of different sizes. The results showed no statistically significant difference between the two vibrotactile feedback configurations (amplitude-modulated and position-modulated stimulation) for grip force. However, with vibrotactile feedback, the percentages of correct grip forces were significantly higher than those with no feedback. The same could be observed for hand aperture feedback.

The authors concluded that subjects with upper limb loss improved performance when receiving either grip force feedback or hand aperture feedback in the virtual grasping tasks. However, the two feedback configurations were not tested simultaneously. Therefore, the authors suggest that future studies should evaluate which feedback configurations might be optimal when providing multi-channel feedback.

Effects of Vibrotactile Feedback and Grasp Interface Compliance on Perception and Control of a Sensorized Myoelectric Hand[9]

Pena *et al.* recently investigated the potential benefits of vibrotactile sensory substitution concerning the quality of perception and control of grip force and hand aperture of a myoelectric hand prosthesis. Similar to the work of Witteween *et al.*, they compared the performance of two different configurations for providing vibrotactile sensory substitution; a single voice coil actuator and an array consisting of five coin tactors. For the first configuration, a single linear C2 actuator was placed on the ventral side of the forearm, distal to the elbow. The actuator was used to create oscillations perpendicular to the surface of the forearm, and it was activated using bursts of square wave pulses, as illustrated in the diagram labeled **A** in Figure 3.2. By decreasing the burst width and interval between bursts – termed BW and IBI (inter-burst interval) in the figure, respectively – the frequency and duty cycle of the stimulation are increased. This results in increasing stimulation intensity levels, which can be mapped to the full range of grip force or hand aperture of a prosthetic hand.

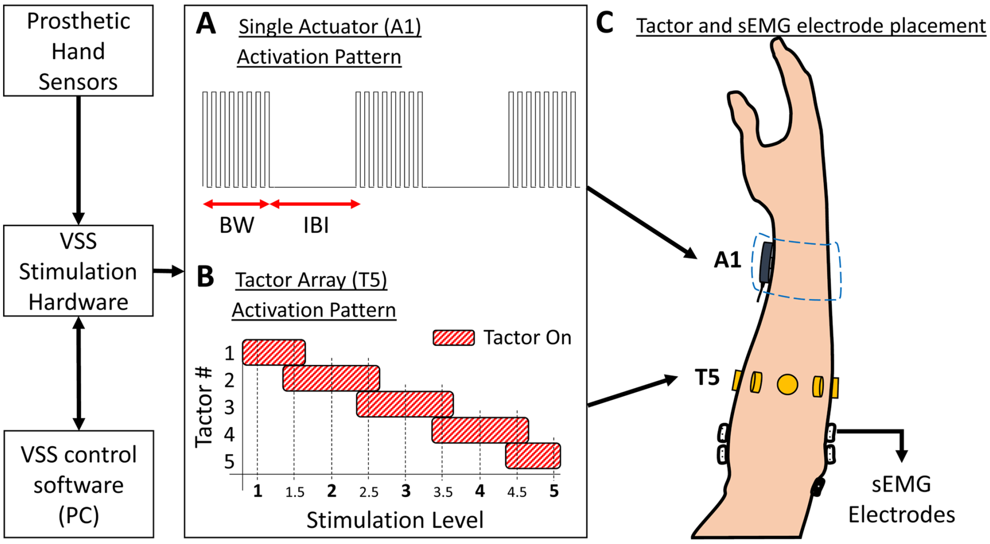


Figure 3.2: Vibrotactile sensory substitution configurations. "A1" is the linear actuator, while "T5" is the array of coin motors. From [9]

Instead of using an array of eight coin motors, like Witteveen *et al.*, the second configuration is limited to only five coin motors. The type of coin motors used in this study is an eccentric rotating mass (ERM) brushless vibration motor with a peak frequency of about 250Hz. The array was placed around the forearm, proximal to the elbow. In order to create a sensation of the stimulus moving across the arm, the coin tactors were activated in an overlapping pattern. This is illustrated in Figure 3.2 by the diagram labeled **B**. The overlapping activation pattern was used to create nine sequential signal levels, each of which can be mapped to a level of grip force or hand aperture of the prosthetic hand.

16 able-bodied subjects participated in experimental tasks involving the control of a myoelectric hand prosthesis. Surface EMG electrodes were placed on the subjects' forearm to target the flexor and extensor muscles. The prosthetic device was equipped with both grip force and hand aperture sensors, and placed out of sight. A screen displayed virtual grip force and hand aperture targets, as well as the grip force and hand aperture applied by the subject. Based on the feedback provided by either the linear actuator or the coin motor array, the subjects were to control the hand prosthesis to reach the target grip force or hand aperture.

In the target-hitting task for grip force, the subjects performed significantly better when receiving feedback from the coin motor array compared to when receiving feedback from the linear actuator. No significant difference was observed between the two feedback configurations when subjects received feedback about hand aperture. The authors suggest that future studies should evaluate the simultaneous use of grip force and hand aperture feedback.

Non-Invasive, Temporally Discrete Feedback of Object Contact and Release Improves Grasp Control of Closed-Loop Myoelectric Transradial Prostheses[18]

Clemente *et al.* identifies several reasons for "the shortage of successful results" of providing feedback for grip force in a prosthetic hand. They point out that feedback is usually provided in a continuous manner, even though humans have a tendency to adapt to continuous stimuli. Instead, the authors suggest that the feedback should be event-triggered. They, therefore, propose a feedback device that delivers short sensory cues in the form of bursts of vibrations to the user. The proposed device consisted of two parts; sensorized thimbles to be placed on the digits of a myoelectric prosthesis, and an arm-cuff equipped with vibration motors. The thimbles were embedded with force sensors, and the arm cuff provided bursts of vibrotactile feedback based on the force measured by the sensors. Figure 3.3 illustrates how the prosthetic device's grip force triggers tactile events in a pick-lift-replace manipulation task. A tactile event is triggered when the prosthetic hand makes contact with the object, when the object is lifted (the total measured force increases), when the object is put down (the total measured force decreases) and when the prosthetic hand breaks contact with the object.

In order to evaluate the effectiveness of the feedback device, five subjects with transradial amputation participated in a "Virtual Eggs Test". The test required small, fragile boxes, representing eggs, to be transfered from one side of a 15cm tall obstacle to the other using the prosthetic hand. The subjects' performance was measured by the percentage of broken boxes, as well as the rate of which the subjects transfered the boxes over the obstacle. Over the course of five weeks with one test session per week, results of the Virtual Eggs Test showed a statistically significant decrease in the percentage of boxes broken. This could imply that the

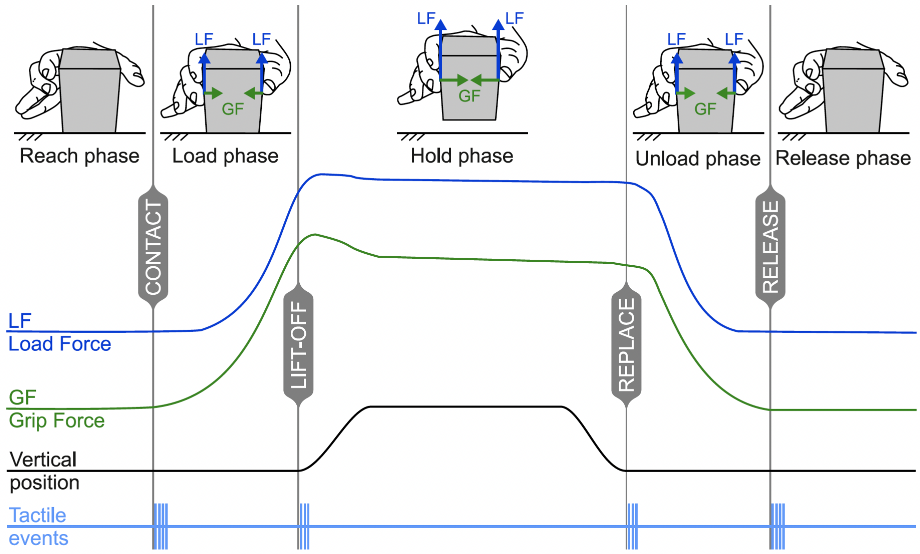


Figure 3.3: Illustration of the tactile events triggered by the phases of a pick-lift-replace manipulation task. From [18].

subjects improved their sensorimotor control. Howeever, there was no statistically significant decrease in transfer rate.

The authors believe that it would be possible to use any stimulation modality – for instance electrotactile, pressure or vibrations – without compromising the effectiveness of the feedback device, given that the stimulus is event-triggered.

Closed-Loop Control of Grasping With a Myoelectric Hand Prosthesis: Which Are the Relevant Feedback Variables for Force Control?[19]

Grasping force is a recurrent feedback variable for closed-loop control of hand prostheses in the literature. It is considered an intuitive and logical choice since it provides feedback about the variable that is being controlled[1]. However, as Ninu *et al.* points out, force production is only the last step in a grasping process. Force feedback has in previous studies been transmitted based on measurements from internal or external force sensors, meaning that the feedback is "activated only after the hand comes in contact with an object". However, force production depends on the steps following the event of coming in contact with the object.

To evaluate which are the most important variables for force control feedback, the authors evaluated the performance of 13 subjects in controlling grip strength through varying the feedback variables when doing a complete grasping sequence. Feedback variables included variables that characterize the state of the prosthesis, like closing velocity, first contact with an object and grip force. The

[1]Not to be confused with modality matching, which provides feedback that is *similar* to the information it is conveying.

feedback variables were provided by either vibrotactile stimulation or visual feedback. The results showed that the subjects were able to control grip strength by estimating the grip force from the prosthesis' closing velocity, and the experiments demonstrated that direct force feedback was not essential for controlling the grip force.

A Novel Method to Generate Amplitude-Frequency Modulated Vibrotactile Stimulation[20]

To the author's knowledge, few studies attempt to provide multiple pieces of sensory information through a single feedback channel. As already discussed, the work of Ninu *et al.* [19] evaluated feedback variables related to grip force in a sequential manner. Similarly, Clemente *et al.* [18] used vibrotactile feedback to provide event-triggered information to the user. However, neither address the need for simultaneous feedback. Dosen *et al.* propose a device that generates vibrotactile stimulation by simultaneously modulating the amplitude and frequency of the vibrations. They designed a vibrotactile transducer able to produce stimulation signals with independently controlled amplitude and frequency.

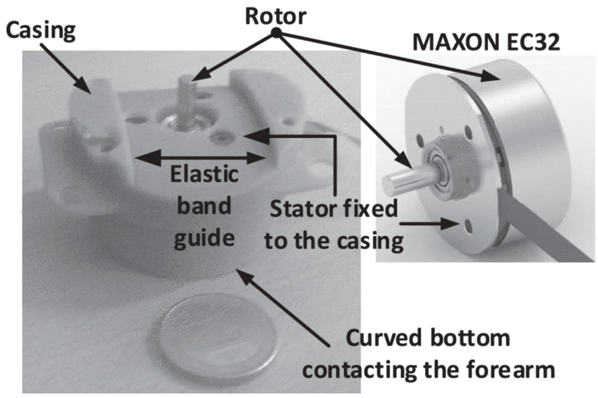


Figure 3.4: Device used to generate different patters of amplitude and frequency modulated vibrations. From [20].

The proposed device, depicted in Figure 3.4, uses a rotary electric drive to spin a balanced weight about a rotational axis. The vibrations result from the rotor's acceleration and deceleration about its rotational axis. When the rotor turns back and forth, the stator reacts with equal and opposite forces, causing it to rotate about the rotational axis of the rotor. Since the stator is fixed to the casing, this motion produces vibrations that stimulate the skin by stretching it tangentially in a rapid back-and-forth motion.

Results from a psychophysical[2] experiment with four healthy subjects showed that the device could produce approximately 400 discernable stimuli – each called

[2]"A psychophysical experiment seeks to determine whether the subject can detect a stimulus, identify it, differentiate between it and another stimulus, or describe the magnitude or nature of this difference"[21].

a "vixel" – through different amplitude and frequency combinations. This allowed the authors to generate a large variety of vibrotactile patterns. The authors suggest that evaluating the device in a functionally meaningful scenario, such as prosthesis control, would be the next step.

Tactile Feedback in Closed-Loop Control of Myoelectric Hand Grasping: Conveying Information of Multiple Sensors Simultaneously via a Single Feedback Channel[22]

Following the concepts presented by Dosen *et al.*, the goal of Mayer *et al.* is to verify whether using a single channel of vibrotactile feedback can be used to convey two pieces of information simultaneously. A challenge with vibrotactile feedback is that its perception depends on the force with which the actuator or transducer is pressed against the skin – it is said to be static-force dependent. However, the same research group has earlier found that vibrotactile feedback applied over bony landmarks does not suffer from this static-force dependency[23]. Since there are few bony landmarks in the human upper limb, Mayer *et al.* proposed an approach where a vibrotactile transducer is worn on the elbow bony landmarks. This approach attempts to verify whether subjects can differentiate between two pieces of encoded sensory information based on vibrotactile feedback received via a bone conduction channel.

Ten able-bodied subjects performed experiments consisting of three different tasks situated within a virtual reality environment. The first task – a grip force regulation task – consisted of applying a target grip force level to a virtual object. The grip force was controled by EMG surface electrodes targeting the flexor and extensor muscles of the subject's forearm. The EMG signals controlled a virtual prosthesis grasping the virtual object. Based on the grasp force produced by the subject, vibrotactile feedback was provided to the subject's elbow through a vibrotactile transducer. The vibrotactile feedback had a fixed stimulation frequency, while the amplitude was modulated as a linear function of the grasp force signal.

The second task involved classifying secondary information from the vibrotactile feedback when the amplitude of the feedback signal remained constant. The subjects were to report whether the feedback contained a low, medium or high level frequency component. A third, mixed task combined the first two tasks to evaluate the subjects' performance when being provided with two pieces of information through the vibrotactile transducer simultaneously. The subjects had to execute grip force regulation and then report on the perceived frequency stimulus.

The results showed that the subjects were able to distinguish between the two pieces of information provided through the vibrotactile transducer. However, the performance was slightly worse when the subjects received both pieces of information simultaneously compared to the tasks where only one piece of information was provided.

Touch Feedback and Contact Reflexes Using the PSYONIC Ability Hand[24]

Akhtar *et al.* claim to have shown that prosthesis users are able to grasp delicate objects without damaging them when provided with contact reflexes and vibration feedback.

The Ability hand is sensorized with pressure sensors on each digit. “The sensor providing the highest pressure value is mapped to a vibration motor whose amplitude changes with the pressure applied.” In order to test the efficacy of the sensory feedback, two subjects with below-elbow amputations performed a series of grasping tasks – a cup grasping task and a hollow eggshell grasping task. When providing touch feedback to the subjects, a “contact reflex” is activated in the prosthetic hand. The contact reflex causes the hand to automatically stop when contact with the object is made. Four feedback conditions were tested; 1) with touch feedback and with visual feedback, 2) with touch feedback and without visual feedback, 3) without touch feedback and with visual feedback, and 4) without touch feedback and without visual feedback.

The results show that, for the cup grasping task, there is a statistically significant difference between the feedback conditions with touch feedback and the feedback conditions without touch feedback. There is no mention of the difference between feedback conditions 1 (with touch feedback and with visual feedback) and 2 (with touch feedback and without visual feedback). Cups are deformed significantly less when touch feedback with contact reflexes are provided. Similarly, with the hollow eggshell grasping task, a better performance was seen when the subjects were provided with touch feedback and contact reflexes. On the contrary, when touch feedback with contact reflexes were turned off, the eggshells were usually cracked. Touch feedback without contact reflexes was not tested, so the results do not say whether it was the vibrotactile feedback or the contact reflexes that resulted in better performance during the grasping tasks.

3.2.2 Mechanotactile feedback

The Rice Haptic Rocker: Skin stretch feedback with the Pisa/IIT SoftHand[10]

Battaglia *et al.* introduced the Rice Haptic Rocker, which is a skin stretch device for providing proprioceptive information – more specifically hand aperture – through stretching the skin with the use of a mechanical rocker with frictional contact. A model and prototype of the Rice Haptic Rocker are depicted in Figure 3.5. The device consists of a 3D printed frame, a Velcro strap, a rocker and a servo motor. The feedback device is integrated with the Pisa/IIT Softhand, which is a 1-DOF prosthetic hand. The rocker features a frictional interface to the skin, and together with the rocking motion, the device aims to provide an intuitive cue when mapped to the hand aperture. When the hand is completely open, the rocker is in its neutral position. As the hand closes, the rocker rotates up to 60 degrees, thus imposing a proportional stretch on the skin.

In order to investigate the effectiveness of proprioceptive feedback from the

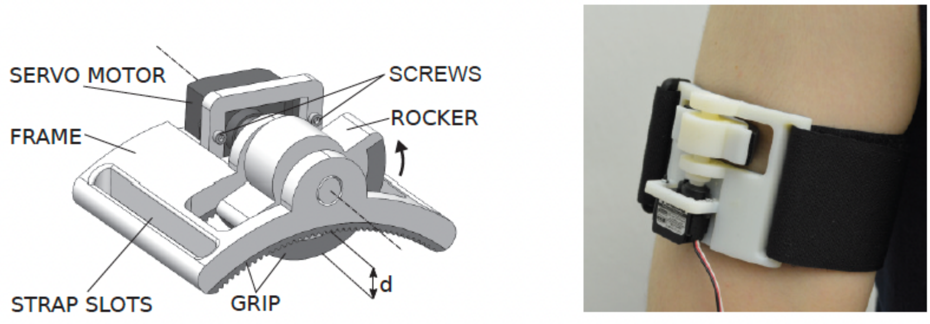


Figure 3.5: The Rice Haptic Rocker. Left: CAD model and parts. Right: Physical prototype on the upper arm of a subject. From [10].

Rice Haptic Rocker, an experiment with 18 healthy subjects was conducted. The experiment consisted of an object discrimination task, where the subjects were to discriminate between different spherical sizes. One group consisting of nine of the subjects conducted the task while receiving haptic feedback from the Rice Rocker, while the rest of the subjects did not receive any haptic feedback when performing the task. The average accuracy for subjects who received haptic feedback from the Rice Rocker while completing the object discrimination task was 73.3%. For subjects who did not receive haptic feedback, the average accuracy was 33.3% – in other words, they performed no better than chance. The difference in discrimination accuracy was found to be statistically significant, and the authors concluded that “the Rice Haptic Rocker enabled the subjects to detect a difference in object size with better accuracy than chance”.

The Rice Haptic Rocker: Comparing Longitudinal and Lateral Upper-Limb Skin Stretch Perception[11]

Following the promising results of Battaglia *et al.*, Clark *et al.* investigated subjects’ performance in a target hitting task with two orientations of the Rice Haptic Rocker. The authors hypothesized that receiving feedback through skin stretch in the longitudinal direction would be more intuitive than skin stretch in the lateral direction.

To test their hypothesis, the authors had 23 able-bodied subjects participate in a virtual target-hitting task. The task involved moving a cursor on a screen to a given position using two keyboard inputs while receiving feedback from the Rice Rocker. The feedback device was placed on the subjects’ upper arm, and both the arm and feedback device were occluded from vision. The rocker’s position on the arm was moved proportional to the cursor on the screen. The cursor was only visible during training, whereas during the assessment, the subjects had to rely solely on the haptic feedback from the Rice Rocker to position the (invisible) cursor at the desired location on the screen.

As expected, receiving feedback through skin stretch in the longitudinal direction resulted in smaller errors compared to skin stretch in the lateral direction. The authors suggest that this is due to the fact that longitudinal stretch is more easily discerned than laterally oriented stretch. During limb movement, stretch about joint angles occurs in the longitudinal direction. Therefore, imposing feedback through skin stretch in the longitudinal direction is believed to be more intuitive since it mimics the manner in which skin stretch occurs naturally.

A Wearable Skin Stretch Device for Haptic Feedback[25]

Bark *et al.* present a feedback device that transmits localized skin stretch. The device is designed to provide feedback on non-glabrous skin and consists of an end effector with two circular pads with double-sided skin-safe adhesive. A model of the skin stretch device is shown in Figure 3.6. The contact pads have two configurations – fixed or free – to account for the different skin strain patterns imposed when rotating the end effector. "Local shear strains imparted by rotation of the pads can cause a stronger sensation of intensity but can also become uncomfortable for large rotations." However, freely rotating pads can make it difficult to detect small rotations.

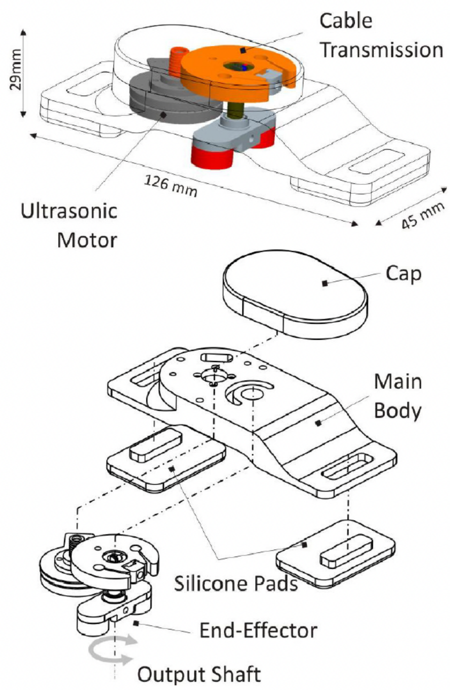


Figure 3.6: Model and expanded view of the rotational skin stretch device. From [25].

Two experiments assessed ten subjects' ability to detect the rotation from the skin stretch device. In one experiment, the subjects performed an active positioning task where they were to orient the device to match the orientation depicted on a screen. In the other experiment the subjects were to report the perceived orientation of the device when sitting passively while the device rotated autonomously. The experiments showed that the device is effective in closed-loop tasks where the feedback is correlated to user movements or commands, as in the active positioning task. However, the subjects performed poorly for the passive perception task and had trouble distinguishing in which direction the skin stretch device was rotating.

Passive Mechanical Skin Stretch for Multiple Degree-of-Freedom Proprioception in a Hand Prosthesis[26]

Akhtar *et al.* present a passive linear skin stretch device for providing proprioceptive feedback in a prosthetic hand. The device, depicted in Figure 3.7, consists of three contact pads adhered to the forearm of the subject. The contact pads are connected to pulleys, which are mounted onto the servo motors of the thumb, index and middle fingers of a prosthetic hand so that when a subject moves a digit on the prosthetic hand through EMG signals, the corresponding contact pad will pull on the skin of the subjects' forearm.

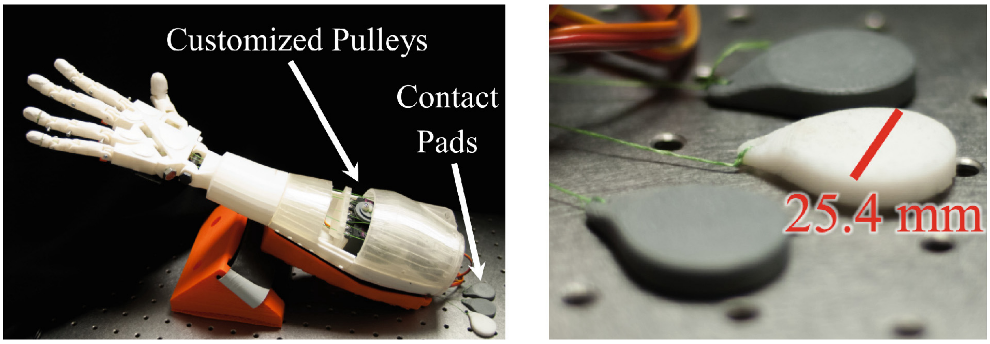


Figure 3.7: Passive linear skin stretch device consisting of contact pads attached to hand prosthesis. Adapted from [26].

The authors compared the skin stretch device to a feedback case with a vibrotactile array and a no-feedback case through two different experiments. The first experiment was based on a single-DOF virtual finger task, where subjects were to move a virtual finger on a screen by flexing or extending their metacarpophalangeal joints, which were measured through EMG. This task tested three feedback conditions: vibrotactile feedback, passive linear skin stretch feedback, and no feedback. The resulting difference between no feedback and vibrotactile feedback, as well as the difference between no feedback and skin stretch feedback, was found to be significant. There was no significant difference between vibrotactile feedback and skin stretch feedback for this task.

The second experiment consisted of two multiple-DOFs tasks: a grip recogni-

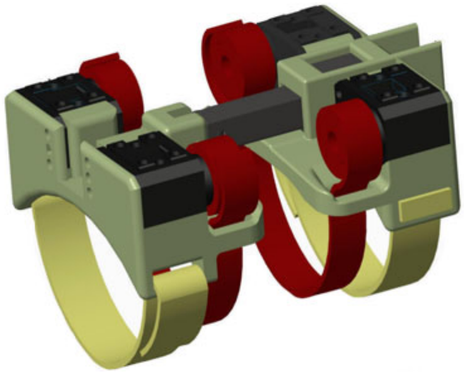


Figure 3.8: A CAD model of the hBracelet. Adapted from [27].

tion task and a hand aperture targeting task. In the grip recognition task, subjects were to identify specific grips based on skin stretch feedback. The subjects correctly selected 88.0% of the presented grips on average. In the hand aperture targeting task, subjects were to use EMG control to match target apertures at 25%, 50% and 75%, both with skin stretch feedback and without any feedback. The error in percent aperture for the case with skin stretch feedback was significantly lower than that without feedback.

The hBracelet: A Wearable Haptic Device for the Distributed Mechanotactile Stimulation of the Upper Limb[27]

Though not used for prosthetic hand applications, the haptic device proposed by Meli *et al.* is demonstrated to be effective in providing haptic feedback through mechanotactile stimulation in a teleoperation scenario. The authors attest to that the device can successfully provide information about forces acting at the remote site and that this can also have its applications within sensory feedback for trans-radial prosthetic hands.

The device – called the hBracelet – consists of four servo motors, two belts and a linear actuator, all mounted on a 3D-printed frame. A model of the device is shown in Figure 3.8. Through pressure and stretch cues related to normal, tangential and longitudinal forces, the hBracelet is designed to provide multimodal mechanotactile stimulation to the upper limb. In particular, a squeezing force is exerted when motors that share the same belt spin in opposite directions, as the belt then applies pressure on the subject's arm. When the motors sharing a belt spin in the same direction, a shear force is applied as the belt will stretch the skin on the subject's arm. The two belts of the hBracelet are controlled independently, meaning that the device can produce shear forces along different directions. This generates different cutaneous sensations. For example, if both belts are rotated in the same direction, the device produces a tangential force which provides a shearing sensation. On the other hand, a wringing effect can be produces if the belst are rotated in opposite directions. Additionally, the linear actuator can be used to apply longitudinal stretch and longitudinal squeeze by bringing the belts further apart or closer together, respectively.

Ten healthy subjects participated in an experiment mimicking a teleoperation scenario. The subjects were to control a 7-DOF robotic gripper arm equipped with force sensors while receiving haptic feedback from the hBracelet. The subjects controlled the robotic arm through keyboard inputs without direct visual feedback. The robot's average gripping force was mapped to the normal force of the hBracelet by squeezing the subject's arm proportional to the average gripping force. One of the tasks consisted of gripping an object by increasing the grip force of the robotic arm until the subjects could feel a stable squeezing force. When the robotic arm reached the force required to grip the object, its grip force could not be increased further.

The results indicate that squeezing exerts a clear stimulus and that it is useful in informing the subject about the force with which the remote object is gripped. Subjects were able to detect when the grip force no longer increased, and over a total of 40 trials, only one miss occurred. When asked about the comfort, the device received an average rating of 6.8 out of 10 from the subjects, and the authors suggest that the device's ergonomics should be improved, proposedly by reducing the number of actuators.

Skin Strain Patterns Provide Kinaesthetic Information to the Human Central Nervous System[12]

Though not a feedback method in itself, the work of Edin and Johansson highlights a critical remark related to mechanotactile feedback. They performed a series of experiments with five healthy subjects where they injected a long-lasting anaesthetic into the proximal interphalangeal (PIP) joint of the left index finger and had the subjects perform matching tasks and pointing tasks. In the matching task, the anaesthetized digit was manipulated by the experimenter and at the same time the subjects were to indicate the posture of the anaesthetized digit by using their normal right index finger. In the pointing task, the subject were to touch the tip of the anaesthetized digit using their normal right index finger after the experimenter again had manipulated the anaesthetized digit. The subjects' hands were occluded from vision during the experiments. The experimenter either manipulated the anaesthetized digit to flex or extend, or induced skin strain patterns on the proximal part of the PIP joint to mimic flexion or extension.

In the matching task, all subjects correctly indicated the extension or flexion of the anaesthetized digit. However, when the experimenter kept the digit flexed, but induced a skin strain pattern similar to that observed when extending a finger, the subjects extended their right index finger. Similarly, when a skin strain pattern mimicing flexion, the subjects flexed their right index finger, even though the experimenter manipulated the anaesthetized digit to be extended.

A similar trend as observed in the pointing task. When the experimenter manipulated the anaesthetized digit to be extended or flexed, the subjects were able to touch the tip of the anaesthetized digit with their normal right index finger. However, when the experimenter extended the anaesthetized digit, but induced skin strain patterns similar to that of flexion, the subjects were unable to touch their left index finger and instead pointed their right index finger to the point where contact would have been made had the left index finger been flexed instead. The same behavior was observed when the anaesthetized finger was flexed, but skin strain patterns associated with extension were induced.

Based on these observations, the authors concluded that "skin strain may be perceived as joint movements rather than skin deformation". They deduced that mechanoreceptors in the skin have precedence over muscle spindle afferents and that the perceived position of finger joints "may be determined by afferent signals generated as a result of movement-associated skin strain patterns".

Chapter 4

Design proposal

Based on the literature presented in Section 3.2, a series of design choices have been made. This chapter presents an evaluation of these design choices followed by a design proposal of a feedback device.

4.1 Purpose

Before making any design choices, the purpose of the feedback device has to be established. The purpose of the device should reflect the most important aspects as redeemed by the literature. According to the literature, there seems to be a consensus about the need for providing more than one feedback channel.[8, 9, 22] Therefore, a choice should be made about the number of feedback channels provided by the device.

A feedback device is of no use on its own if it is not recognized as part of a larger, closed-loop system. A useful feedback device must provide information that is otherwise not present through the intrinsics of the prosthesis itself. According to Aszmann and Farina[1], the user of a prosthetic system is often able to infer the state of their prosthetic device – for example the closing and opening speed of the hand – either based on visual or auditory input or from vibrations in the prosthesis socket. Aszmann and Farina instead point to that sensory information about grip force and hand aperture would be valuable feedback to a prosthesis user. This is also backed by others who suggest that grip force and hand aperture feedback can increase prosthesis embodiment.[2, 4, 6] Consequently, the proposed feedback device should be able to provide sensory stimuli related to the prosthesis' grip force or hand aperture or both. The phrasing "related to" is used intentionally to underline that direct feedback is not essential, as suggested by Ninu *et al.* [19], but that the sensory feedback can also be based on estimated quantities, like closing velocity.

Though neither size nor complexity should have predominance at the prototyping stage, it is desirable for the device to be simple and preferably small enough to be wearable. That being said, size and complexity should not come at the cost of intuitive sensory stimuli, which, all things considered, is the most important aspect of any feedback device. Intuitive sensory stimuli should also be the main focus when considering which feedback method – virbotactile or mechanotactile feedback – to choose.

4.2 Single- or dual-channel feedback?

As mentioned, the design should allow for the provision of feedback for grip force or hand aperture or both. Object manipulation, for example, requires the user to receive information about more than just grip force alone. However, providing all the information necessary to perform object manipulation tasks through a single feedback device can result in an overwhelming amount of stimuli. There seems to be a trade-off between the number of feedback channels and cognitive load. It is already well established that no feedback pose extensive cognitive load on the user of the prosthetic system, as the user will have to continuously watch the movements of their prosthetic device.[2, 4, 5] On the other hand, too many feedback channels can also increase the cognitive load, as the user must interpret the different kinds of sensory stimuli and act based on the information received. Even when providing only two feedback channels through the same device, Mayer *et al.*[22] saw a slight decrease in the subjects' performance.

Another important aspect is that a single device cannot provide multiple feedback channels without increasing in either size or complexity or both. One solution could be to use several devices, but being an amputee there is limited amounts of space on the residual limb where feedback devices can be placed. In order to provide sufficient amounts of information, while not overwhelming the user, it is proposed that the feedback device should allow for the provision of two feedback channels – one for grip force and one for aperture – through the same device.

4.3 Feedback method

Choosing a feedback method is maybe the most important choice of all. This essentially boils down to the question of whether to use modality-matched feedback or sensory substitution. Being more intuitive, modality-matched feedback is often considered superior to sensory substitution.[5, 11] In theory, both vibrotactile and mechanotactile feedback can be modality-matched, although it is easier to implement modality-matched mechanotactile feedback. Regardless of the feedback method, the user of the feedback system must learn to interpret the sensory stimuli. Although sensory substitution with vibrotactile feedback has proven to be valuable when, for instance, performing gripping tasks, Clemente *et al.*[18] points out that it requires substantial amounts of training compared to methods that are considered modality matched.

There is also the concern of desensitization. Some of the mechanoreceptors in the skin are rapidly adapting receptors. This means that when applying a stimulus for a sustained period of time, these receptors will stop responding to said stimuli.

The literature seems to hold the opinion that vibrotactile feedback should *not* be applied continuously for extended periods – up to approximately 60 seconds – if one wants to avoid desensitization.[6, 7, 18] Instead, as suggested by Clemente *et al.*[18], vibrotactile feedback might be more suited to provide event-based feedback where the feedback is given as pulses of vibration to notify the user about the occurrence of a certain event.

The results of Rosenbaum-Chou *et al.*[7] indicate that vibrotactile feedback is limited in its effectiveness of providing feedback about higher-level grip forces. Distinguishing low and medium vibration intensities seem to be easier compared to higher levels of intensity. Some of the cutaneous mechanoreceptors that detect vibrations are very sensitive and have varying receptive fields. Distinguishing some stimulus from no stimulus is easy – either a receptor potential is triggered, or it is not (given that the intensity of the stimulus is above the threshold of perception). However, to tell a medium amount of receptor potentials apart from a high amount of receptor potentials might not be as easy. Although this is an oversimplification of the theory, it can help explain how discerning no stimulus from low- to medium-level stimuli can be easier to perceive. In contrast, intensities above a certain level will be harder to distinguish from the low and medium intensities.

Of particular concern is the stimulation delay of vibrotactile feedback devices. This delay comes at a risk of decreasing the embodiment of prosthetic devices.[4, 6] Before deciding on a feedback method, however, the type of feedback should be discussed in light of the kind of information it is supposed to provide, namely, grip force and hand aperture.

4.3.1 Feedback for grip force

Many have attempted to use vibrations to provide feedback about grip force, with varying results[7–9, 18, 24]. Instead, as already mentioned, Clemente *et al.*[18] suggest that vibrotactile feedback might be more suitable for event-based feedback.

In contrast, few have investigated using mechanotactile feedback for grip force. While the hBracelet designed by Meli *et al.*[27] was originally tested in a teleoperation scenario, the authors recognize the device to be suitable for other applications as well, such as feedback in prosthetic systems. For example, the squeezing effect of the hBracelet proved to be an intuitive method for providing feedback about grip force. However, for use in prosthetic systems, fewer actuators are probably needed. The authors also propose reducing the number of actuators.

To summarize, the results from studies on vibrotactile feedback for grip force are inconclusive, and there seems to be a gap in the literature regarding mechanotactile feedback for grip force. Therefore, the feedback device in this thesis should explore the possibility of using mechanotactile feedback for providing grip force feedback.

4.3.2 Feedback for hand aperture

Edin and Johansson[12] showed that positional information in joints does not rely on muscle spindles alone. Information about a joint's position is also provided by skin stretch, which makes skin stretch a suitable feedback method for hand aperture. This view is also supported by the research group who worked on the Rice Haptic Rocker, Clark *et al.*[11] and Battaglia *et al.* [10]. Also, based on the work of Akhtar *et al.*[26], skin stretch has proved useful for aperture recognition.

In contrast, providing feedback about hand aperture through vibrations is challenging and unintuitive. Although promising results were seen for grip force, the work of either Witteveen *et al.*[8] or Pena *et al.*[9] provides no indication on what kind of vibrotactile feedback configuration is most suitable for hand aperture feedback. Based on this, skin stretch shows the most promising results when providing feedback about hand aperture in prosthetic systems. Consequently, the design of the feedback device should incorporate skin stretch to realize hand aperture feedback.

4.4 Design proposal - Mechanotactile feedback for squeeze and stretch

This design is based on the device proposed by Meli *et al.* [27]. Their device, the hBracelet, includes five actuators that can be controlled independently and therefore supports at least eight different actuation types, including longitudinal stretch, squeeze and shear. The design proposed in this term project, illustrated in Figure 4.1, is a simplification of the hBracelet and only incorporates two actuators. The actuators, being two independently controlled servo motors, are connected to a belt around the subject's arm. By rotating the servos in opposite directions, the belt will tighten around the arm, producing normal forces imposed from the belt to the arm. This causes a squeezing effect and can provide feedback about grip force. If the servos are rotated in the same direction, the belt will slide around the arm, causing tangential forces that will stretch the skin in the direction of rotation. This can be used as feedback on aperture. The applied forces will depend on the frictional properties of the belt and the skin of the arm.

Grip force can be measured by equipping the digits of the prosthetic device with force sensitive resistors (FSRs). Based on these measurements, the servo motors should be rotated so that the belt is tightened a proportional amount. In this way, the squeezing of the arm will be proportional to the grip force of the prosthetic hand. Naturally, some processing unit or other, such as an Arduino[1], is needed to read and process the force measurements and control the servos.

Measuring the hand aperture of a prosthetic hand depends on the type of prosthetic hand in question. For example, some prosthetic devices are equipped with

[1] "Arduino is an open-source electronics platform based on easy-to-use hardware and software." Arduino boards use a variety of different microcontrollers that support a range of features.[28]

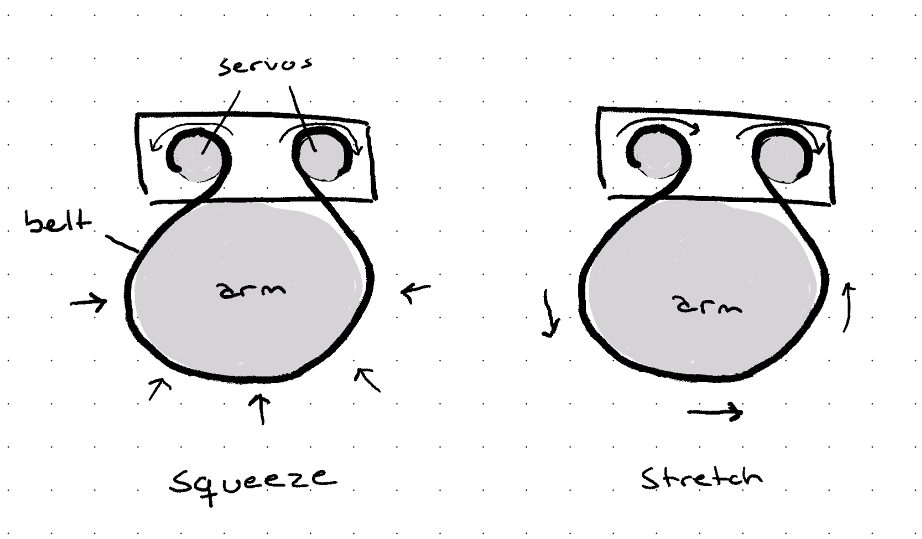


Figure 4.1: A conceptual illustration of the feedback mechanisms of the proposed feedback device.

servo motors to control their digits, and in this case, the hand aperture can be provided from the motor encoders. Other prostheses incorporate pressure measurements from which the hand aperture can be estimated. In any case, as with grip force, the servo motors of the feedback device should be rotated proportionally to the hand aperture such that the skin stretch imposed by the belt is proportional to the hand aperture.

The servo motors used in the original hBracelet are the Dynamixel XL-320, but the proposed design in this thesis can be realized by any type of servo motor that is powerful enough to produce a squeezing effect on the forearm. The belt of the hBracelet is a custom 3D printed thermoplastic polyurethane belt. What kind of material is used for the belt is not of importance, except that it should be comfortable and not completely frictionless. Otherwise, imposing skin stretch will prove challenging.

In order to avoid painful stimuli when providing feedback about either grip force or hand aperture, the servos should not exceed a maximum limit of rotation. This limit should, of course, be determined through a psychophysical assessment before conducting experiments. As suggested by Meli et al., the forces imposed on the skin during grip force feedback should not cause an indentation in the skin of more than approximately 13mm. Additionally, the psychophysical assessment should establish a threshold of perception for the individual users of the feedback device.

Chapter 5

Discussion

This chapter discusses some features and challenges with the feedback device proposed in Section 4.4. Additionally, some limitations regarding artificial feedback, as well as the transferability of results from previous works, are also considered.

5.1 Modality-matched feedback

The design proposed in Section 4.4 has the advantage of being modality-matched. A squeezing sensation around the arm very much mimics the act of grabbing and holding an object. Similarly, skin stretch occurs naturally about a joint when a limb is bent about said joint. Nevertheless, the feedback must still be interpreted by the receiver. Even though a feedback method is modality-matched, correct interpretation of the feedback cannot be guranateed. This can only be verified through conducting clinical experiments.

5.2 Proprioception

Since hand aperture feedback provides information about limb position, it is often associated with proprioceptive feedback. Providing proprioceptive feedback is an extremely challenging task. Recall from Section 2.1.3 that proprioception is “sensed” in the muscle spindles and Golgi tendon organs. However, opening and closing the hand will impose skin stretch about the joints of the hand – the metacarpophalangeal joints – which activates cutaneous mechanoreceptors. Therefore, providing proprioceptive information through skin stretch is seemingly impossible, as the mechanoreceptors that detect proprioception are not the same as ones detecting skin stretch. On the contrary, according to the work of Edin and Johansson [12], afferents that respond to skin stretch seem to have precedence over muscle spindles “with regard to proprioceptive information”.

5.3 Challenges

Mayer *et al.* [22] argue well for the need for simulatenous feedback and point to that delivering only grip force feedback or only hand aperture feedback – even in a sequence – is not sufficient when performing object manipulation tasks. A challenge with the current design is that it does not immediately allow for simultaneous feedback of grip force and hand aperture. However, it should be possible to provide both grip force and hand aperture feedback simultaneously by letting one servo motor rotate faster than the other. Although a much more complex solution, this will, in theory, impose both squeeze and stretch on the skin at the same time. Whether it is easy, or let alone possible, to discern and interpret the sensory information when delivered simultaneously is another case. As already discussed in Section 4.2, providing too much information – even through two separate feedback channels – can impose a high cognitive load on the user.

A drawback with this design is that the stretching of the skin occurs in the lateral direction. As shown by Clark *et al.*[11], skin stretch in the longitudinal direction can feel more intuitive since it mimics the stretch that is naturally applied to the skin around joints when moving a limb. However, given that sufficient training is provided to account for the slight mismatch in skin stretch direction, stretch in the lateral direction can still prove to be effective.

5.4 Limitations

Many who view skin stretch as a suitable method for mechanotactile feedback often cite the work of Edin and Johansson[12]. Though there is evidence that skin stretch is a suitable feedback method in itself, one has to question whether skin stretch in the finger is translatable to skin stretch in, for instance, the forearm, which is usually where the skin stretch is imposed when providing artificial feedback from hand prostheses. The sensory afferent neurons that would otherwise signal the sensation of skin stretch about a finger are no longer part of the peripheral nervous system of a person with a transradial amputation. When an able-bodied person moves their fingers, strain is imposed about the proximal interphalangeal and metacarpophalangeal joints. This activates slowly adapting mechanoreceptors in the skin. Skin stretch imposed on the forearm through artificial feedback is thought to activate the same kind of receptors. Though a similar mechanism of sensory neuron activation occurs in both cases, the two are not guaranteed to be 100% compatible.

For one, the receptive field in different regions of the body varies as a result of different concentrations of cutaneous receptors. Areas with a high concentration of cutaneous receptors have both greater tactile sensitivity and spatial accuracy. The number of cutaneous receptors in the forearm is much lower than those in the hands and fingers. Hence, mapping tactile feedback that is otherwise received by receptors in the hands and fingers to receptors in the upper arm will likely result in a less accurate perception of the feedback.

Though providing artificial feedback aims to restore the sensory stimulation, it is important to emphasize that the feedback, even when modality-matched, cannot fully replace lost functions. The sense of touch, for instance, requires more than feedback about grip force or hand aperture. When touching an object, the different cutaneous receptors of the hand provide information about what is being touched. For example, the type of surface or texture is detected by Merkel disks, while Meissner's corpuscles contribute to detecting the shape of the object. Even when directly stimulating the receptors responsible for a certain tactile sensation through invasive feedback, full restoration of sensory stimuli is an extremely challenging task.[1, 5] A prosthetic feedback device should aim for delivering intuitive sensory feedback that makes prosthetic control uncomplicated. After all, the best prosthetic system is the one that is being used.

Chapter 6

Concluding remarks

6.1 Conclusion

As a consequence of transradial amputation, the natural feedback pathway between the central nervous system and the mechanoreceptors that detect sensory stimulation in the hand is broken. Therefore, providing artificial sensory feedback to users of prosthetic hands is higly important for both prosthesis control and embodiment. The literature highlights the need for providing dual-channel feedback, as, for example, object manipulation requires that the user be provided with sensory information about more than just grip force. Another concern is that the feedback should be intuitive and preferably mimic the natural sensations that occur in the skin during gripping or hand opening and closing. Therefore, the conceptual design presented in Section 4.4 aims to provide modality-matched feedback for both grip force and hand aperture. Grip force feedback is delivered through a squeezing effect imposed on the forearm, whereas skin stretch provides hand aperture feedback. One drawback with the design is that skin stretch occurs in the lateral direction, although prvious work has shown that skin stretch in the longitudinal direction can be more intuitive. Whether this negatively affects the clinical performance of the proposed feedback device remains to be demonstrated, as explained in the next section.

6.2 Future work

It comes without saying that the proposed feedback device should be implemented. This includes creating a more enriched model than the one presented here, as well as making a selection of the materials needed to meet the properties of the design and the model. For example, it is recommended to assess different types of materials for the belt to avoid materials that might cause pain when the belt is squeezing or stretching the skin of the forearm.

In order to evaluate the feedback device's effectiveness in providing feedback for grip force and hand aperture, experiments following a suitable assessment protocol should be conducted. Before testing the device in a real-life setting, the perceived stimuli should be evaluated. This includes carrying out psychophysical tests to identify the average threshold of perception and adjust the forces applied to the skin. When conducting clinical tests with able-bodied subjects, it is suggested that the device's performance be tested in virtual tasks. If the virtual tasks provide promising results, it would be interesting to see whether delivering simultaneous feedback of grip force and hand aperture affects the performance.

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