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Abstract

Intuitive Vibrotactile Feedback Patterns for Upper Limb Prostheses

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Intuitive control resulting from sensory feedback is of high importance for upper limb amputees. Due to the lack of sensory perception, interaction with the environment is a difficult task. In this regard, the objective of this study is to provide haptic feedback in prostheses. Currently, users of prosthetic devices are limited to only visually monitor their performance, which demands a high cognitive effort.

As for methodologies, psychophysical measurements were conducted to identify vibrotactile feedback as a suitable haptic stimulation method and to provide a scaling system of the applied vibration. On that basis, vibrotactile feedback patterns were generated by using the same motor attached to the skin of healthy participants. It employed vibrations within a defined setting with maximum frequency of 60Hz, corresponding to the range of mechanoreceptors in the skin. Pattern generation was inspired by various other disciplines, such as psychology and acoustics as a basis for intuitiveness and familiarity. In that way, pattern recognition and mapping should be quick and easy. Three types of patterns were adopted: static, dynamic and pulsed ones, which differed in amplitude and frequency combinations as well as break time in between one amplitude and frequency display. Those patterns were subsequently evaluated for intuitiveness and preference according to the following prosthetic movements: grip force, position of hand and contact with objects – which resulted in four dynamic movements and four static states. While one pattern was applied, participants could choose between two movements to be coded by it and rate their choice afterwards.

Analysis showed distinct mapping of static patterns to static states and dynamic and pulsed patterns to dynamic movements. Moreover, one pattern per movement could be identified as the most prominent in cast votes as well as rating. This study provides a catalog of patterns to be used as guidance in vibrotactile feedback.

By providing intuitive sensory substitution in the form of vibrotactile patterns to the users, prosthetic control can be improved and resulting cognitive effort in handling be diminished.

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List of Abbreviations

CNS	Central Nervous System
SA	Slowly Adapting
RA	Rapidly Adapting
SDT	Signal Detection Theory
JND	Just Noticeable Difference
WF	Weber Fraction

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Introduction

Losing the sense of touch is an impairment that might not be apparent so at first sight. But without sensory feedback from the skin and the joints, it is difficult to interact with the environment. Grasping a cup of coffee is no longer an automatic or intuitive performance, but instead needs constant visual monitoring and attention. Only by this supervision it is possible to tell the position of the limb and the force of its grip (Goldstein 2010). The gravity of this impairment is illustrated by Cole (1995), who reports of an extreme case of loss of feeling. Ian Waterman, who lost all of his interoception and exteroception from the neck down, needed to visually supervise his every movement. He described this circumstance of constant cognitive effort to be like running a daily marathon (Cole 1995). A further illustration on why sensory feedback is so important in everyday life was given by Monzéé et al. (2003) and Avenanti et al. (2005) in experiments where they temporally anesthetized the hands of healthy participants. Because of the consequential loss of feelings in their hand, they applied much more force than necessary during grasping tasks, and while manipulating an object.

Intuitive control through sensory feedback is still an area of improvement for prosthetic design. This has been identified in recent surveys along with the need for which information should be conveyed by this feedback (Lewis 2012, Biddiss 2007, Kyberd 2007, Kyberd 2011). The most important information for the amputees were grasp (position of hand), hold (grip force), touch (contact with object) and proprioception. The preferred modality of transfer was vibration. Based on these findings, prosthetic designers and developers can be guided by the need of amputees on what information should be measured and how it can be transmitted by the prosthesis.

Up to this date, no commercially prostheses are available that would provide haptic feedback to its user. Still constraining them to solely rely on visual and sometimes unintended auditive feedback when controlling their prosthetic device. However, position of the hand, grip force and contact with an object are impossible to tell without constant visual surveillance. Aside from that, there are other hardships prostheses' wielders may face. Due to the lack of sensation in the missing limb, it might not be felt as part of one's own body and is henceforth disintegrated from bodily awareness. The prosthetic device might even be doomed to negligence due to missing efficacy and intuitiveness (Antfolk 2010). Evidence indicates that user acceptance of artificial limb prostheses would be significantly enhanced by a feedback system which provides appropriate, graded, distally referred sensations of touch and proprioceptive joint movement (Dhillon 2005).

By employing haptic technologies, the independent sensory system of the human physiology is efficiently exploited as a communication channel. An additional information is delivered which enhances the user's experience of a multimodal environment (Hale 2004). The knowledge gained about user demands and the progressing technical capabilities can be combined to develop a haptically supported interface that decreases cognitive load and in turn increases user friendliness. Vibration is a common modality used to induce such haptic feedback. It has the advantages of being adaptable in size, having relatively little power consumption and it is easy to implement by adopting readily available mobile phone motors or piezoelectric actuators. Moreover, the user acceptance rate in contrast to electrical stimulation is much higher. Vibrotactile feedback is a feasible method to

provide sensory haptic feedback and shall be further explained and investigated in the course of this thesis.

Overview and Content Explanation

This thesis consists of eight main chapters, from introducing the background of upper limb prostheses and motivation for sensory feedback to the final conclusion on what kind of feedback to implement with a proposal for a certain catalog of mapped movements and vibration patterns.

In the first chapter, background information about upper limb prostheses and their users is given. User demands are considered for what feedback modality is of interest for them and by which modality it should be conveyed. A state of the art of arm prostheses shall help understand their basic operation methods and situation of amputees. In the next chapter, various sensory feedback modalities are explained to give an overview of what is technologically possible. An idea of what is physiologically possible is found in the third chapter, where human skin physiology is explained in regard to vibrotactile feedback. Also the psychological aspects of vibrations are considered. The main theme of intuitiveness is introduced therein. The whole chapter four is dedicated to explain vibration in depth while profiting from thought-provoking impulses inspired by various other disciplines such as engineering, biology, psychology and acoustics. In the following methodology section, the main psychophysical methods Signal Detection Theory and Two-Alternative Forced-Choice Task which are used in the two subsequent experiments are thoroughly explained. The first experiment with its set up, procedure, analysis and results is described in chapter five. It is a psychophysical measurement to identify vibrotactile feedback as a suitable haptic stimulation method and to provide a scaling system of the applied vibration. The second experiment specified in chapter seven is directly based on these findings, as it employs a certain stimulation range detected by the previous experiment. It results in a catalog of vibration patterns, whose generation was inspired by aspects of different disciplines mentioned in chapter three and consecutively evaluated in an experimental setting. The last chapter poses as an overall recapitulation of the topics and experiments treated in this thesis and provides a discussion and future perspective on the development of sensory feedback for upper limb prostheses.

1 Background

First attempts of supporting prostheses with a feeling of touch and implementing sensory feedback mechanisms into artificial limbs date back to the late 1950s. The following 35 years were marked by rather slow research progress, but recent years have shown an enormous gain in interest and research activities in the area of tactile displays and the integration of haptic signals into prosthetic devices (Jones 2008). User demands are increasingly taken into consideration during the process of tactile display design as well as physiological characteristics of the human body.

1.1 User Demands

Commercial arm prostheses lack the ability to transmit sensation, either from the environment or within one's own body. But according to a survey by Sören Lewis (2012) among users of electrical upper limb prostheses, receiving sensory feedback was rated of absolute and medium importance by 88% of respondents (Lewis 2012). Already in 1996 (Atkins 1996) and 2007 (Biddis 2007) surveys revealed that sensory feedback would improve prosthetic control. Diane Atkins (1996) actually focused on evaluating everyday usage of prostheses and found out about the desire to lessen visual attention while operating the prosthesis.

Elaine Biddis (2007) reported that the current feedback of electrically controlled prostheses is insufficient. Which makes sense, as there is none except the noise generated by the motor and the feel of the shaft against the skin. The only sensory methods to obtain feedback are therefore essentially visual and to a certain unintentional extend auditive.

Elaborating these previous findings, Lewis' (2012) survey addresses the following questions: Is sensory feedback of interest to users? Which information should be conveyed and by which method should this information be applied? A total of 108 amputees completed the digital survey, which consisted of rating scales and free text entries. It is composed of 42 questions structured into four parts: (1) satisfaction with current prosthesis, (2) demands for sensory feedback, (3) phantom phenomena and (4) general data on participants, including information about their amputation and prosthetic use.

The most important information wished to be conveyed was grip force, closely followed by receiving feedback about the prosthesis' position. First contact and last contact with an object was also highly rated. These statements make sense if thought of how to grasp a glass - one does not want to break the glass by applying too much force, neither does it make sense to close the hand while the glass is still not within our reach. This also shows in the results of the importance of sensory feedback during everyday tasks: the most important activities during which people want to receive feedback were during grasping and holding objects, followed by general manual work and eating with cutlery. Surprisingly, dressing and personal hygiene are done without the prosthesis, rendering feedback unnecessary (Lewis 2012).

Vibration, pressure, electrical stimulation and temperature were the selected methods for transmitting the above sensory information. The actual implementation though relies on the acceptance and sensitivity at the residual limb as well as the technological possibilities. Temperature is a delicate choice: Even though it was highly rated as preferred method of transmission, residual limbs are mostly insensitive to temperature. Thus, this

could be the desire to retrieve the former ability of thermic sensation, but this method is not suited to transmit sensory feedback. The most promising method as to convey sensory information seems to be vibration. Electrical stimulation interferes with the myoelectrical control system of the prosthesis, whereas patients are equally insensitive to pressure as to temperature (Lewis 2012).

1.2 State of the Art: Upper Limb Prostheses

Losing an upper limb can have several reasons. Among acquired losses of a limb, the most prominent ones are accidents, diseases or battlefield injuries. There is also the likelihood of congenital absence of a limb or congenital malformation. It impacts activities of the daily live and and its quality. However, no matter how elaborate the construction of a prosthesis, behaviour and functionality of a real hand can only partially be restored (Näder 2011). On that account, the demand to design a prosthesis combining both naturalistic functionality and inconspicuous appearance is yet to be fulfilled.

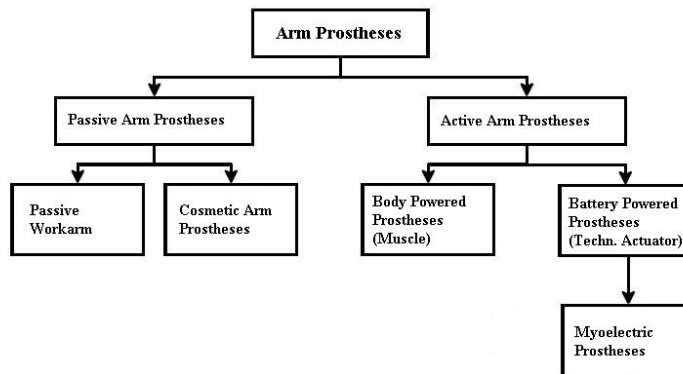


Figure 1.1: Classification of Arm Prostheses (Näder 2011)

Figure 1.1 roughly illustrates the current classification of arm prostheses. Passive (also called static) arm prostheses are further divided into cosmetic prostheses and work arm prostheses. Cosmetic prostheses only aim at mimicking the outward appearance of a real hand without providing any functionality. They can look utterly realistic, but are also hard to keep clean (see Figure 1.3). Workarm prostheses possess a certain predefined functionality and are to be operated with the other hand. Functions that can be restored to some extent are moving the arm or joint and manual grasping through the use of active (also called dynamic) arm prostheses. Because every upper limb amputee has lost their hand, grasping is placed with special importance. The body powered prostheses exploit muscle contraction of the shoulder belt to transmit this force through a cable connected to the prosthetic device, that could, for example, either be a split hook or a mechanical hand. This type of prosthesis delivers indirect sensory feedback by forwarding reaction forces through the cable back to the body, as illustrated in Figure 1.2 (Näder 2011, Antfolk 2013). They are of moderate cost and weight and are the most durable prostheses. However, they are not as aesthetically pleasing as their battery powered counterparts and elicited movements are rather rough (Micera 2010).

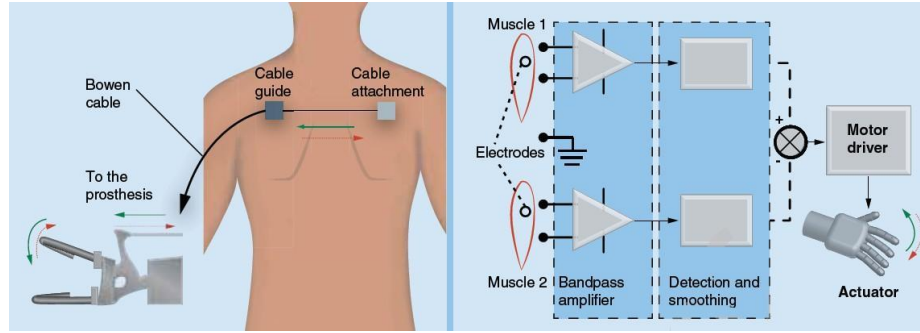


Figure 1.2: Body and Battery Powered Prostheses (Antfolk 2010:2)

Myoelectrically controlled prostheses make use of muscle contractions in the residual limb or a targeted nerve reinnervation site. The electromechanical components in battery powered myoelectric prostheses are moved by action potential signals generated by antagonist muscles and recorded through surface electrodes. Those signals are processed to control the arm, hook or hand to a varying degree of freedom of the intended prosthetic movement. It is powered by integrated rechargeable batteries. The more distal an amputation, the more degrees of freedom the prosthesis needs to cover. For a transhumeral¹ patient, three joints need to be controlled: Elbow, wrist and hand. Thus with every degree of freedom, myoelectrical control using the conventional two electrodes increases in difficulty (Näder 2011, Antfolk 2013). For those cases, a control command is necessary to initialize a certain movement. Grip force and speed are both estimated from the intensity of the EMG signal (Micera 2010). The “two most distributed powered hand prostheses are those made by Otto Bock (Germany) and Touch Bionics (U.K.)” (Micera 2010:50). However, while still providing decent moving and grasping functionality helped establish the myoelectrically controlled prostheses as a standard, administering sensory feedback is still an open issue. Besides for the incidental stimulation through socket pressure or motor sound and vibration (Antfolk 2013).

Type	Main Advantages	Main Disadvantages
Cosmetic	Most lightweight Best cosmesis Less harnessing	High cost if custom-made Least function Low-cost glove stains easily
Body powered	Moderate cost Moderately lightweight Most durable Highest sensory feedback Variety of prehensors available for various activities	Most body movement needed to operate Most harnessing Least satisfactory appearance Increased energy expenditure
Battery powered (myoelectric and/or switch controlled)	Moderate or no harnessing Least body movement needed to operate Moderate cosmesis More function-proximal areas Stronger grasp in some cases	Heaviest Expensive Complex maintenance Limited sensory feedback Extended therapy time for training

Figure 1.3: Comparison of Upper Limb Prostheses (Micera 2010:50)

1.3 Control Circuit - Open and Closed Loop

Control of the prosthesis by now is only achieved by visual monitoring and incidental stimulation, but except for research environments not through design intention (Antfolk 2013). That kind of system corresponds to an open loop control. Now with the use of sensory feedback the concept of closed loop control can be achieved.

¹amputation level: upper arm below the shoulder

Voluntary movements are goal-oriented intentional movements that “improve with practice as one learns to anticipate and correct for environmental obstacles that perturb the body” (Kandel 2010:656). To act on those perturbations, sensory signals from the limbs are monitored and that feedback information is used by a controller to direct further movements of the actuator. In the motor system control operated by feedback, signals transferred from sensors are compared with a reference signal which is the desired output state, as illustrated in Figure 1.4. The difference in those two states is consequently used to adjust the output. A closed loop is a dynamic system whose parameters are altered by a change of the reference signal or input. If the task is, for example, to hold a ball, the controlled system is the hand, the sensors are the mechanoreceptors in the skin that feed back information about position and grip force, and the muscles are the actuators which are given the reference signal that designates the required muscle contraction to maintain the ball within the hand (Kandel 2010). In an open loop, it is only possible to send out commands, but not to receive feedback about how it affected to object.

Exteroceptive and proprioceptive information used in closed loop control would increase the performance of manipulating objects with a prosthesis. In this regard, a prosthesis should detect interaction with the environment as well as sensing its joint position and feed it back in a perceivable, useful, intuitive and effortless way (Antfolk 2013).

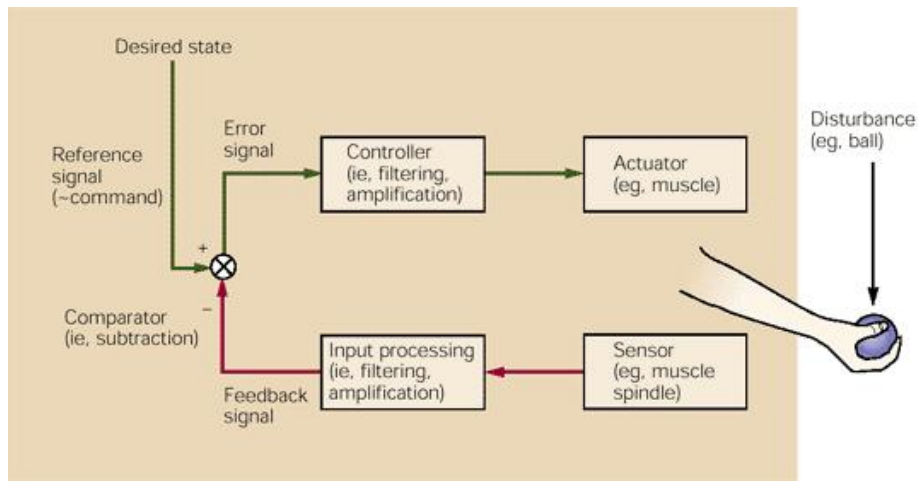


Figure 1.4: Feedback Control (Kandel 2010:655)

New devices with a sensor built within the prosthetic hand have been developed to adequately and automatically control object manipulation and hand grip. For example, if the Sensorhand Speed invented by Otto Bock senses a change in object behavior within the hand’s grip, e.g. slipping, an automatic grip force regulation mechanism comes into place that increases the grip force to keep the object from slipping out of the grasp (Näder 2011).

2 Sensory Feedback

Amputees are deprived of their sense of touch and proprioception due to the missing limb. Residual nerves and muscles cannot provide the needed sensory feedback a healthy limb could. Providing that missing sensory functionality is still a challenge for prosthetic developers (Antfolk 2013). Sensory feedback in body powered prostheses is quite comprehensible, as it is delivered by force or movement exerted by the prosthesis onto the amputee’s residual limb (Micera 2010).

Receptors in the body provide natural feedback to sense information from the surroundings (exteroception) and the body posture (proprioception). Those somatic receptors are divided in cutaneous and subcutaneous mechanoreceptors, muscle and skeletal mechanoreceptors, nociceptors and thermoreceptors, to provide the central nervous system (CNS) with four basic corresponding modalities: touch, proprioception, pain and temperature (Antfolk 2013). After the loss of those receptors, transmission of stimuli to the CNS has to happen a different way. This can be done invasively by interfacing directly to the nerves in the peripheral nervous system or noninvasively by outsourcing the feedback to an intact sensory system, e.g., the residual limb, the upper arm or the chest. Either way, patients provided with any of the sensory feedback methods need to be trained to associate incoming signals with the actual stimuli (Antfolk 2013).

Several different techniques have been exercised to provide amputees with sensory feedback: 1) direct neural stimulation of the peripheral afferent nerves, 2) modality matched feedback that behaves like the actual stimulation at a different place and 3) sensory substitution, where the stimulation is translated into another modality and as well to be perceived at a different place. Inherent to all mentioned techniques is the crucial aspect of timing, which is needed to encourage a feeling of embodiment within the user (Antfolk 2013).

Sensory feedback research mainly focuses on myoelectrically controlled prostheses and can be identified to belong to one of the following categories: 1) Investigation of new devices or techniques by using psychophysical methods, 2) Testing existing sensory feedback systems in already prevailing force or position paradigms, and 3) Applied clinical studies that employ feedback systems in functional grasping tasks (Antfolk 2013).

2.1 Modality Matched Feedback

A feedback is called modality matched when the output stimulus is congruent with the modality of the sensory input. For example temperature on the prosthesis is felt as temperature on the receptor area. The modality matched feedback method was pursued by researchers because associating a sensation to the stimulus is intuitive and effortless. However, reproducing this natural sensation is a challenging task, though matching the modality can be accomplished by using noninvasive methods. Therefore actuators equivalent to the modality are placed onto the skin, usually at the residual limb. For instance in temperature transmission, electromechanical components are connected with thermoelectric components (Davalli 2000, Antfolk 2012).

2.1.1 Mechanotactile Feedback

Mechanotactile feedback is a form of feedback where force applied to the prosthesis is conveyed in the same modality to the user’s skin. This can be achieved, for example, by a pusher placed on the residual limb. The behaviour of the actuator should resemble the force felt by the prosthesis and provide a sufficiently high resolution. Shortcomings of this type of feedback are the timing, since the system takes a certain time to be initiated. Also weight and energy consumption are still of concern (Antfolk 2012, 2013). Meek et al. (1989) embedded force sensors into a myoelectrically controlled prosthetic hook and used a servo-controlled pusher connected to it by a cable to deliver feedback proportional to that received in the terminal device. The authors called this approach “extended physiologic taction” (Meek 1989). Kim et al. (2010) developed a multi-function haptic display that conveys modality-matched touch, pressure, vibration, shear force and temperature (Kim 2010).

2.1.2 Direct Neural Stimulation

Electrically stimulating afferent nerves originally innervating the fingers, hand and palm with implanted electrodes should theoretically recover modality matched somatic sensory information (Antfolk 2013). In 2005 Dhillon and Horch have implanted electrodes within individual nerve stumps in amputees and demonstrated that through these electrodes it is possible to regain graded, discrete sensations of touch or movement in regard to the patient’s phantom hand. Amputee’s could judge both joint position and grip force in the prosthesis, without visual monitoring (Dhillon 2005). In a previous study done by Clippinger (1974), patients could successfully correlate grasp force and information gained through direct neural nerve stimulation. However, even though different types of electrodes have been used, such as cuff electrodes that are wrapped around the nerve (Clippinger 1974) or longitudinal intrafascicular electrodes that are placed inside the nerve longitudinally (Dhillon 2005), the reported quality of sensations was an unfamiliar feeling. Those sensations included paresthesia, vibration or various pressure sensations on the skin. These phenomena could arise due to the incapability to address selected neural interfaces and bundles of different afferents are contacted together. Hence different types of mechanoreceptors would all respond at the same time (Antfolk 2013). In general, direct nerve stimulation for sensory recovery functions similar to methods used in noninvasive electrotactile stimulation. Except the threshold for electrical charges to induce sensation is lower in direct neural stimulation by one to two orders of magnitude (Rossini 2010, Antfolk 2013).

2.2 Sensory Substitution

Sensory substitution is the transfer of a stimulus modality into a different one than normally used. Thus one sensory channel is compensated or substituted by another, e.g. to substitute vision with touch, or touch with hearing, or the same channel is used but the modality differs, e.g. to substitute pressure with vibration (Antfolk 2013). Because the receptors needed for physiologic sensory transmission are lost in amputees, sensory substitution is a method often employed in upper limb prostheses. The most popular approaches are electrotactile and vibrotactile substitution, which present to the skin

electric currents or vibrations respectively to convey information about joint position, grasp force or movement direction (Antfolk 2013).

2.2.1 Electrotactile Feedback

Electrotactile sensory stimulation (also called electrocutaneous stimulation) evokes potentials in the afferent nerve endings through the application of an electrical current on the skin surface (Antfolk et al. 2013, Kaczmarek et al. 1991). Though the current is administered locally, the elicited sensations do not necessarily be confined to that skin region but can spread if sufficient enough nerve fibers or bundles are activated (Kaczmarek 1991). Electrotactile stimulation can either be current or voltage modulated. Current-modulation is indifferent to changes in the tissue load and impedance at the electrode interface, whereas voltage-modulated stimulation lowers the risk of skin injuries due to high current densities (Antfolk 2013).

Electrotactile stimulation properties are: current amplitude, pulse waveform (biphasic/monophasic, rectangular, sinusoidal), pulse frequency and duration of pulse burst (Antfolk 2013). Typically, the current ranges within 1-20mA with a pulse frequency from 1-5000Hz. More comfortable sensations are elicited by biphasic pulses compared to monophasic ones (Antfolk 2013, Szeto 1982). Saunders (1973) found out, that the threshold charge was constant at 62nC regardless of the pulse repetition frequency (60-200Hz) across a range of 1-20mA of current amplitudes and 1-100µs pulse duration time (Saunders 1973).

Qualitatively, subjects described electrotactile sensations as “a tingle, itch, vibration, buzz, touch, pressure, pinch, and sharp and burning pain, depending on the stimulation voltage, current, [...] waveform,” as well as on the “electrode size, material [...] and contact force, and the skin location, thickness and hydration” (Kaczmarek 1991:4).

Stimulating the afferent nerve fibers with electrodes evokes the same sensation qualities associated with the activation of those nerve types. For example, a tactile sensation can be elicited by directly stimulating the responsible receptors in the skin (Vallbo 1981). But not all sensations are comfortable. Kaczmarek (1991) proposed the useful intensity range of electrotactile stimulation to be a ratio of the threshold of pain to the threshold of sensation - P/S. It is a function of electrode size, material, placement and the parameters of the stimulation waveform. The pain/sensation current ratio varies from 2dB to 20dB at most and is thus far behind the range of the ear (120dB) or the eye (70dB) (Kaczmarek 1991).

As identified by Lewis (2012), relevant information to be conveyed to the prostheses' users are grip force and proprioception. To code these conditions, electrotactile stimulation was provided by altering the amplitude of the pulses (Lundborg 1998), the frequency and the rate of pulse bursts (Lundborg 1998, Wang 1995, Shannon 1979) to one or multiple stimulation sites (Tupper 1989, Antfolk 2013). “Amplitude modulation was shown to be superior to pulse rate modulation in conveying grip intensity, however pulse rate modulation was less susceptible to adaptation” (Antfolk 2013:4).

Advantages of electrotactile devices are their low power consumption and faster response than that of vibrotactile systems, as there are no mechanical parts needed to put in motion (Antfolk 2013). However, the compatibility with myoelectric prostheses is pro-

foundly decreased when the stimulation electrodes are placed near the control electrodes (Meek 1989). Different techniques are being examined to solve this problem (Sasaki 2002).

2.2.2 Vibrotactile Feedback

Vibrotactile feedback utilizes mechanical stimulation on the skin surface to induce vibrotactile sensations. The typical stimulation frequencies range between 10 and 500Hz (Kaczmarek 1991). The main parameters that can be modulated according to different information within vibrotactile feedback are amplitude and frequency, as well as beat interference, pulse duration, shape and duty cycle (Antfolk 2013, Cipriani 2012, Jones 2008).

In 1953, vibrotactile feedback was first introduced to prosthetic applications by Conzelman et al. (Conzelman 1953) and has been looked further into since then due to its high compatibility with myoelectrically controlled prostheses and greater compliance rate among users compared to electrotactile stimulation (Shannon 1976, Kaczmarek 1991). Twenty years after Conzelman’s first proposition, Mann et al. (1970) designed a kinesi-
thetic sensing system to feed back proprioceptive information about the angle of the elbow joint of the myoelectrically controlled Boston Arm by using vibrotactile actuators. Their results showed an improvement in precision and accuracy in position tasks (Mann 1970). Bach-y-Rita and Collins (1970) developed a vibrotactile sensory substitution device that transfers sensory input to the patient’s back or to the residual limb through an array of vibration motors (Bach-y-Rita 1970). Vibrotactile displays are an affordable solution nowadays. Vibration motors used to be costly and bulky, but those drawbacks have been overcome and subtle, low-power consuming motors are available off the shelf. Vibrotactile systems have been embedded in various myoelectric upper limb prostheses for research purposes. Otto Bock (Sensorhand Speed, Michelangelo), Touchbionics (i-Limb) and Motion Control (Motion Control Hand) rank among the contributors (Saunders 2011, Sears 2008, Chatterjee 2008).

2.2.3 Other Sensory Substitution Methods

There are also other sensory substitution methods that have been investigated to provide the necessary sensory information. Gonzales et al. (2012) recently explored the feasibility of employing an auditory display by using psychophysical measurements. With the auditory substitution method, it is possible to code individual finger positions with different sound cues (Gonzales 2012) or modulate the pitch, timbre or volume of an auditory signal to convey grip force or hand position (Antfolk 2013). Wheeler et al. (2010) presented a haptic sensory substitution device, that provides information about position and motion by inducing rotational skin stretches (Wheeler 2010).

3 Aspects to Consider for Vibrotactile Feedback

Generally speaking, independently from the characteristics of structural criteria, humans may perceive vibrations very differently. What is comfortable for one person, may be bothersome to another. This perception is influenced by positioning, whether a person is lying down, sitting or standing up. If there is movement involved, vibrations are less likely to be noticed and seen as disturbing. Even though common grounds exist in physiological and psychological comprehension, individual aspects have to be considered when dealing with human sensations and perceptions, especially with amputees whose receptors might not behave in a calculable way.

3.1 Vibration

Vibration is everywhere around us. Whether one takes the train to work, sits in a building or listens to music. Those are examples for both the vibration of air and mechanical vibration (Lalor 1998). While only mechanical vibration will be considered from here on, the connection to acoustics will take a special place in one of the later chapters.

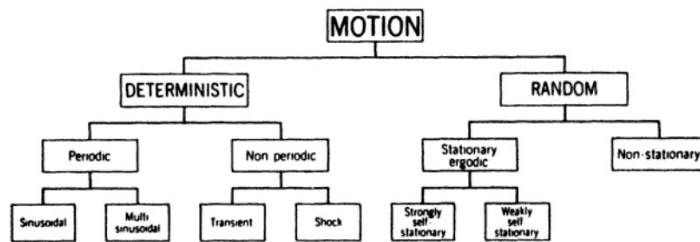


Figure 3.1: Types of vibration (Griffin 1996:4)

The oscillatory motion can be either random or deterministic as illustrated in Figure 3.1. Though only the deterministic motion will be of further interest. It can be subdivided into periodic, which harbors sinusoidal and multi sinusoidal motions and non periodic, which harbors transient and shock motions. Examples for each of these types of vibration are shown in Figure 3.2.

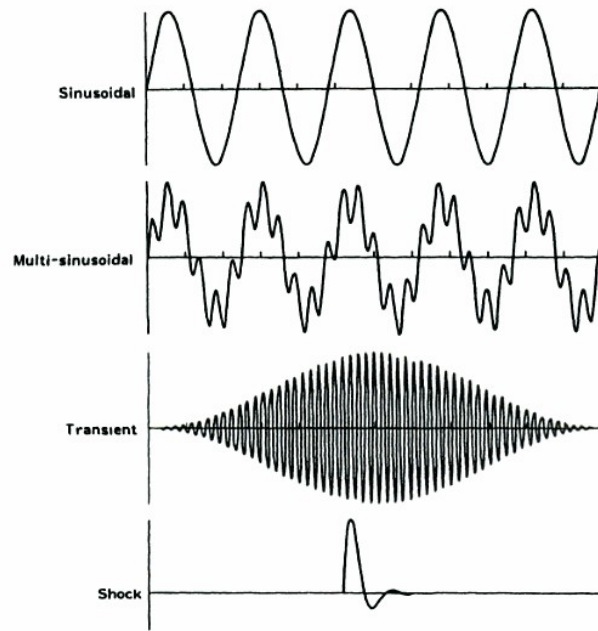


Figure 3.2: Different Oscillatory Motions (Griffin 1996:6)

There can also be different modes of vibration. Depending on the vibrating object, there are vibrational modes possible which can be transversal, longitudinal and rotational.

If the vibration repeats itself at regular intervals, it is called periodic. Periodic vibrations can be fractionized into their basic components, the sine waves through a Fourier analysis, which is needed in order to study the structure of the vibration². Periodic vibration in most cases is produced as a resonance frequency of a certain object and thus lasts for quite a long time, due to the long decay time of a frequency at resonance.

Depending on the way it is produced, periodic vibration can be split in two different kinds: free vibration and forced vibration. When a vibratory system experiences a displacement, it starts to oscillate at its resonance frequency, which is used for example in musical instruments (strings). This is called a free vibration, as the object tends to vibrate at this frequency on its own. An object can have many resonance frequencies, which can be excited. If the displacement is in time with the resonance oscillation, the vibration builds up.

Because of the natural damping of vibration, forced vibrations normally last only as long as their power sources are active. Example sources for forced vibrations are spin-dryers, or in the case of desired vibration, vibration motors (mostly with an unbalanced weight). Several types of vibration motors exist, which produce forced vibration, for example the motor used in the study described in chapter 5. There are a lot of different sources for vibration. Nearly every motion implicates some sort of vibration, which is often caused by friction. As movement is not perfectly smooth, due to roughness of the surface, there are time varying forces between the objects. They cause a non constant acceleration and thus a vibration. Anyhow, vibration occurs in everyday life, just sometimes not noticeable, such as the swinging motion of buildings. . This swinging

² in the frequency domain

of a building is an unwanted motion, leading to instability or, such as the vibration of a motor, wasting energy. Looking at this, vibrations can also cause damage, depending on material, frequency and location. Therefore, limits for vibration exist in work regulations as overly exposure to certain vibrations can lead to an occupational disease (Lalor 1998).

However, there are a lot of cases which require vibration. Music is of course only possible if one is able to deliberately generate periodic vibration. Here, the resonance frequencies of strings or more complex objects are used to create the desired vibration. The object is excited to vibrate in its resonance frequency due to a mechanical displacement or an air flow. For acoustics as well as haptics it is important to have a fine tuning of the vibration. In order to drive a speaker or a vibration motor with the desired vibration, a transfer from an analog electric signal into a mechanical vibration is needed. There are different ways to achieve this, each way with its own benefits and drawbacks. For vibration motors, there are advantages and disadvantages manifesting in the elicited vibrations.

Additionally, in a different field, research suggests that a cat's vibratory purr is beneficial to the health. This was reported by the University of Minnesota Stroke Center, that conducted a study that showed a 40% less chance to have a heart attack when owning a cat (Qureshi 2009).

3.2 Physiological Aspects

Vibrotactile sensation is "produced by sinusoidal oscillation of objects placed against the skin. Vibration may be produced by the hum of an electric motor, the strings of a musical instrument, or a tuning fork used in the neurological examination. Mechanoreceptors in the skin respond to these oscillations by a pulse code in which each action potential signals one cycle of the sinusoidal wave" (Kandel 2000:437). In this sense a receptor's response is measured by the change in the firing rate of action potentials by the corresponding afferent nerve fibers (Vallbo et al. 1984). With over 10000 parallel channels, the human tactile system is capable of processing information presented as short as 10ms (Bach-y-Rita 1972).

The human somatosensory system incorporates various types of mechanoreceptors sensitive to touch and vibration of different frequencies and thresholds, of which some are found only in hairy skin or glabrous (hairless) skin. A schematic distribution can be seen in Figure 3.3. Receptors in the glabrous skin include Meissner's corpuscles, Merkel disk receptors and bare nerve endings. In the hairy skin, different hair receptors are found, the hair follicle for example that here take the position of Meissner's corpuscle, as well as Merkel disks and bare nerve endings. The subcutaneous receptors, beneath both hairy and glabrous skin, are Pacinian corpuscles and Ruffini endings. Highest tactile sensitivity is found in the glabrous skin, that contains a dense matrix of mechanoreceptors (Kandel 2010, Bauman 2010). Further receptor characteristics include receptive field size and slow or rapid adaptation (SA and RA) (Kandel 2000, Kaczmarek 1991). Slowly adapting receptors answer to a static stimulus with a sustained discharge of consistent frequency, whereas rapidly adapting receptors spike in the beginning and quickly reduce their activity. SA receptors code for the stimulus intensity while RA receptors react to alteration of it (Bauman 2010). An exhaustive overview of all receptor types can be

found in Figure 3.5.

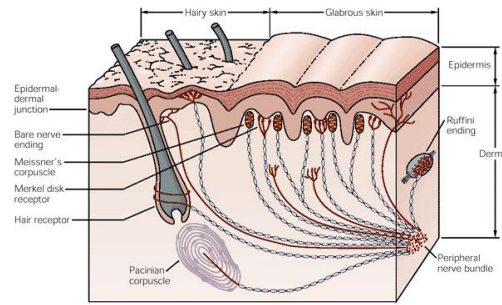


Figure 3.3: Location and Morphology of Mechanoreceptors in hairy and glabrous Skin (Kandel 2010:433)

The three mechanoreceptors most sensitive to vibration are Merkel disks, Meissner corpuscles and Pacinian corpuscles. Most responding to extremely low frequencies are the slowly adapting Merkel disk receptors (5-15Hz), the rapidly adapting Meissner's corpuscles are most responsive to midrange stimuli (20-50Hz) and sensitive to high frequency vibrations are the also extremely rapidly adapting Pacinian corpuscles (50-400Hz, especially sensitive to 50-200Hz), that register the alteration in speed of mechanical stimuli, or "on - off" signals (Bauman 2010). Though Pacinian corpuscles only respond to rapid imprints on the skin instead of constant pressure, they are also able to sense vibration occurring several centimeters away from the actual receptor ending (Kandel 2010). A graph of skin indentation and activation frequency of Meissner's corpuscles and Pacinian corpuscle can be seen in Figure 3.4.

Another slowly adapting mechanoreceptor, though it is not as directly related to vibration as the other three mechanoreceptors are, is the Ruffini ending that responds to skin stretch and continuous pressure in both glabrous and hairy skin and thus contributes as well to the placement of a vibration motor on the skin (Kandel 2010, Goldstein 2010).

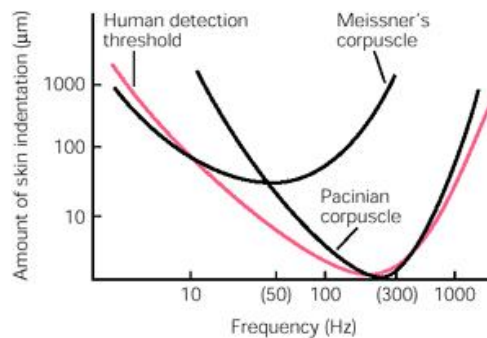


Figure 3.4: Sensitivity Thresholds of Skin Receptors (Kandel 2000:437)

Applied stimuli are temporally integrated and the corresponding receptors are activated synchronously to fire simultaneous action potentials. Thus the resulting intensity is dependent on the number of active sensory receptors. Whereas the vibratory frequency is dependent on the frequency of firing. For example, a vibration at 250Hz is near the threshold of the Pacinian corpuscle, and only those are activated at the area of stim-

ulation. With increasing amplitude also more distant Pacinian corpuscles, as well as Meissner's corpuscles, are activated. Thus, the active receptors are directly proportional to the vibratory amplitude (Kandel 2000).

Geldard (1972) conducted a study to determine the sensation thresholds for vibrotactile stimulation using a 1cm² vibration motor applied at various body locations. Most sensitive to a vibration of 200Hz are the fingertips, while the abdomen is 60 times less sensitive. Weinstein (1968) found, that the thresholds for women are three times lower for the least sensitive locations than those for men.

Another sense involving mechanoreceptors is the proprioception - the sense of one's own stationary limb and body position as well as their movements (kinesthesia). "These sensations are important for controlling limb movements, manipulating objects that differ in shape and mass, and maintaining an upright posture" (Kandel 2010:443). There are basically three types of mechanoreceptors in the muscles and joints that signal the position, speed and direction of the limb: spindle receptors in the muscle for length, speed and stretch of it, Golgi organs within the tendons that sense contractile force of muscles, and joint capsule mechanoreceptors that report about flexion or extension of the joint (Kandel 2010). But also the mechanoreceptors in the skin contribute to proprioception. The Meissner corpuscle that is located close to the skin surface is active when a stimulus is first applied, e.g. first contact with an object, and again when it is removed, e.g. end of contact with an object, assisting to control hand grip (Goldstein 2010).

Receptor type	Fiber groups ¹	Fiber name ¹	Modality
Cutaneous and subcutaneous mechanoreceptors			
Meissner's corpuscle	A α , β	RA	Touch
Merkel disk receptor	A α , β	SAI	Stroking, fluttering
Pacinian corpuscle ²	A α , β	PC	Pressure, texture
Ruffini ending	A α , β	SAII	Vibration
Hair-tylotrich, hair-guard	A α , β	G1, G2	Skin stretch
Hair-down	A δ	D	Stroking, fluttering
Field	A α , β	F	Light stroking
Thermal receptors			
Cool receptors	A δ	III	Skin stretch
Warm receptors	C	IV	Temperature
Heat nociceptors	A δ	III	Skin cooling (25°C)
Cold nociceptors	C	IV	Skin warming (41°C)
Nociceptors			
Mechanical	A δ	III	Hot temperatures (>45°C)
Thermal-mechanical	A δ	III	Cold temperatures (<5°C)
Thermal-mechanical	C	IV	Pain
Polymodal	C	IV	Sharp, pricking pain
Muscle and skeletal mechanoreceptors			
Muscle spindle primary	A α	Ia	Burning pain
Muscle spindle secondary	A β	II	Freezing pain
Golgi tendon organ	A α	Ib	Slow, burning pain
Joint capsule mechanoreceptors	A β	II	Limb proprioception
Stretch-sensitive free endings	A δ	III	Muscle length and speed
			Muscle stretch
			Muscle contraction
			Joint angle
			Excess stretch or force

¹ See Table 22-2. ² Pacinian corpuscles are also located in the mesentery, between layers of muscle, and on interosseous membranes.

Figure 3.5: Receptor Types for Somatic Sensation (Kandel 2010:432)

3.3 Psychological and Cognitive Aspects

Sensation and perception are two different but related processes that base on external and internal stimuli. While sensation describes the detection of input supplied by somatic receptors, perception is the process that consciously makes sense out of these sensations. The information gained by detecting stimuli through a response of corresponding receptor nerves of a sensory organ is electrically transmitted to the central nervous system. While sensations are uninterpreted stimuli, perception refers to the awareness of those sensory impressions. By understanding the sensory information, perception helps to navigate

around the world, to make decisions and to prepare for actions (Carlson 2010, Goldstein 2010).

The sensory haptic system is closely linked to body movements. Gibson (1966) described that the world around the body is explored by using it and that haptic sensory perception is active exploration (Gibson 1966). Combining the concept of haptic sensory perception and the philosophical theory of the extended mind (Chalmers 1998), which states that the mind reaches further than just the bodily boundaries of the skin and that objects can be utilized as an extension of it, then also tools like prostheses can be seen as part of the mind, with all its perceptions. The sensory experience and thus also the perception are transferred to and from that tool. This corresponds to the concept of prosthetic limb control called extended physiological proprioception, authored by D. Simpson (1972). It states that tools like a prosthetic limb act as a mechanical extension to a natural system, the human body. Simpson offers the comparison to a golfer's club or the cane of a blind person as examples. In handling the cane, proprioceptive information about the environment arise in the extremity guiding it. Through those natural sensations in the cane, the person is able to perceive its static and dynamic characteristics (Doubler 1984). Thus the tool becomes an artificial extension of the person's body (Simpson 1972).

Because in myoelectrically controlled prosthesis direct sensory feedback and proprioception is not possible, sensory substitution methods need to claim the part of transmitting the necessary information to the device's operator, hence promoting the concept Simpson proposed of extended physiological proprioception.

The approach of sensory substitution is possible if taken into consideration the representation of stimuli in the brain. Sensory information is stored globally, which means that one perception can be called forward by different senses (Goldstein 2010). The combination, coordination and integration of two different senses into one entity is called intermodal perception. Examples are to look at the person who currently speaks, or mapping a siren sound to a rushing ambulance, both combining visual and auditive sense (Goldstein 2010). Research has proven that this ability is innate, as it can be performed even by newborn infants (Kaye 1994). At any rate, it is possible to recognize a stimuli through a sense different to the one the stimuli was presented to. The sound of a siren will be internally matched to a picture of an ambulance. For vibrotactile sensation, this means that even if the mapped motion to the vibratory feedback is not observed, only by the tactile senses the corresponding movement can be identified.

3.3.1 Intuitiveness

Intuitiveness can be seen as a multidimensional concept, that, because of its elusive nature, is still subject to empirical and theoretical research among psychologists and cognitive scientists.

Psychologist Carl Jung characterizes persons who rather act on intuition³ to be of an "intuitive type". He furthermore describes intuition in terms of a mean to understand possibilities with an emphasis on implications of past and future experiences. "Strongly

³Intuition is to be understood as a predecessor for the word "intuitiveness", which was not a common term during Carl Jung's times (1875 - 1961). In the following text, "Intuition" and "intuitiveness" can be seen as equivalent (Turner 2008).

intuitive people add meaning to their perceptions so rapidly that they often cannot separate their interpretations from the raw sensory data”, they “integrate new information quickly, automatically relating past experience and relevant information to immediate experience” (Frager 2005:56). Intuitive thinking and its courses of action appear to be volatile because it is often based on the unconscious. As opposed to analysis which is attributed to conscious logical reasoning and mental simulation. Actions based on conscious reasoning are called intentional (Klein 2003). Combining the latter two approaches of a distinction between intuitive and analytical acting, Kast (2007) defines two variants of intuitiveness: one based on emotional responses and one based on reasoning. In this sense, information is primarily unconsciously processed and the conscious part only adds to it when the unconscious presents an answer (Kast 2007). Of interest for applications would be the intuitiveness of usability. It has been described by researchers dealing mostly with human computer interfaces as an ease of use or learnability, that is consistent with previous experiences and familiar in a comfortable way, or in a sense that pre-existing skills of the user or resemblance to the real world are exploited, either with direct mapping or by adopting a metaphor (Turner 2008, Bewley et al. 1983, Hix and Hartson 1993, Shneiderman 1992, Raskin 1994). “In everyday usage, intuitive means automatic or without requiring conscious thought” (Turner 2008:475), relying on the affective rather than the rational in responding to circumstances of the world while remaining unaware of the reasons behind that response (Westcott 1968).

Looking further into the literature, the term “intuitiveness” is accredited with essentially three dimensions of distinct but coinciding meaning. These three dimensions are intuitiveness due to familiarity, embodiment and action perception coupling (Turner 2008). Turner states, that familiarity provides an epistemic core for intuitiveness on which a modified action perception coupling is based, a concept pioneered by American psychologist and philosopher William James (1842-1910) and further developed by Maurice Merleau-Ponty (1908-1961), which asserts that it is through the body, people comprehend the world (Turner 2008).

Familiarity

A key contributor to the bonding of intuitiveness and familiarity is Raskin (1994), who puts both terms on the same level. He claims that an interface is intuitive to the degree that it resembles something already known, hence something familiar. In this sense, familiarity is a thorough knowledge, retrievable without effort (Raskin 1994). From a philosophical standpoint, Heidegger (1889-1976) explains that to exist in the world, is to be in it, and framed that fact in the term of being-in-the-world, which should be thought of as a living together and handle the environment. He states, that familiarity is a consequence of simply being in this world and not being able to be separated from this certainty (Heidegger 1985). “In short, we are able to cope with the world and the systems it comprises because we are familiar with it” (Turner 2008:477). This coping is a result of familiarity, “which itself is not conscious or intended but is rather present in [an] unprominent way” (Heidegger 1985:189). Turner (2004) argues, it is not only the knowledge or the creation of it that leads to familiarity and thus intuitiveness, but rather the change in perception.

Embodiment

Intuitiveness reflects embodiment. Whitehead describes in his book *Science and the modern world* that the somatic states regulate human perception and cognition of the world. Therefore “the unity of the perceptual field [...] must be a unity of bodily experience” (Whitehead 1925:91). Merleau-Ponty (1962) adds, that the body is bound to the world, corresponding to what Heidegger proposed as well, and translating it to a different but interconnected concept. Dreyfus (1996) furthermore developed a subdivision of embodiment into three different interpretations. The first interpretation is about the physical dimensions of the body and to identify its innate condition of quantitative capacities and qualitative abilities. The second interpretation deals with everyday life and the practice it provides to improve performance when handling objects and circumstances adjacent to and around the body. The third interpretation revolves around how perception is dependent on embodiment. “Thus our bodies determine how we perceive and interact with the world [through] innate structures, basic general skills, and cultural skills” (Turner 2008:478).

Action Perception Coupling

Action Perception Coupling describes the process in which action and perception are contingent upon each other, in a way that perception provides the means for action as it interprets the incoming sensory data, and action therefore is a necessity for perception, because without moving the body there would not be a lot of new sensation. Bertenthal explains, that this kind of coupling is necessary to adequately respond to given situations. He illustrates that with an example, that walking around and coordinating one’s own movements is not possible without sensory and perceptual information providing supporting updates about the environment. Just a curb would lead to frustration (Bertenthal 1997). “We must perceive in order to move, but we must also move in order to perceive” (Bertenthal 1997:223). Wartofsky (1979) noted, that the environment is shaped by the nature of the perceptual activity, and vice versa, that the perceptual activity is shaped by the environment. By the environment which is shaped according to perception, he speaks of artefacts, objects created by a conscious human activity, developed over usage. Those artefacts now embody human intentions (Wartofsky 1979)⁴.

To summarize and taking into consideration the dimensions mentioned above, intuitive systems employ pre-existing action perception routines on socially defined artefacts, which reduces the cognitive load. The knowledge acquired previously allows the user to directly start using a certain artefact, without spending time on figuring out how to interact with it (Turner 2008). Intuitiveness can subsequently be defined as acting, recognizing or perceiving without immediate cognition through relating the pre-given context to existing concepts.

3.4 Psychoacoustics

Psychoacoustics is a field in which meaningful types of vibration can be found. It is described by its basic terms of sound, tone, beat, roughness, consonance and dissonance.

⁴ An artefact example that reflects action perception coupling is Nintendo’s Wii-mote controller, which is shaped so it can take the form of many of the used pieces of sports equipment, a racket, a golf club or a sword among others. It also feeds back movements by eliciting vibrations in given contexts.

While the latter terms will be explained in detail in the following paragraphs, it is important to priorly stress the difference of the meaning of sound in this context. A sound is regarded as a general acoustic phenomenon, while sounds possessing complex structure are termed tones. Tones have several auditory properties, some of which can be transferred to vibration stimuli induced in the skin.

3.4.1 Time Independence and Time Dependence

Time Independent Auditory Properties of a Tone

As a start, only constant tones shall be of interest and the time dependency is introduced later on. A constant tone is characterized by its frequency spectrum, in which the tone is broken down in its sine wave components by applying a Fourier analysis. The amplitude of the frequencies in the spectrum describes their relative loudness, whereas the main frequency, the one with the highest amplitude, describes the pitch of the tone. The absolute height of the amplitudes is related to the perceived loudness.

The frequency spectrum of tones shows different forms and shapes. Discrete frequencies make up the pitch and the overtones and are important for describing the roughness later on. Also visible within the spectrum is a background shape, depending on the source of the tone. This characteristic, which can be related to the way it is produced, and the propagation in the environment, is called the timbre.

An important aspect of tones that are played by musical instruments or that are produced by vocal chords, is their harmonic structure. Harmonics are the multiples of the pitch frequency, which surmount the other frequencies in the spectrum to form a harmonic series of conjoint frequencies. This is a critical property of a tone and leads to the way how tones interfere to create beat or roughness phenomena.

Other general properties of sounds ⁵ are the duration of the sound, the location where it comes from and also the distance at which it is perceived (Cariani 2009).

Time Dependent Auditory Properties of Tonal Sequences

Taking a sequence of tones, there exist more complex properties to be analyzed. Rhythm for example, is such a property. It is important as it represents the temporal organization of events. Long patterns can be formed which consist of a sequence of tones to be repeated.

Mnemonics are a fundamental method especially in regard to learning and intuitiveness. Mnemonics thus are elements which are easily remembered, for example the ring tone of a telephone. As such, they can possess aspects of familiarity or novelty. Moreover, a sound can also have other cognitive associations, which is then called semantics. It is dependent on context and cultural meaning. This could be for example the sound a beeper makes while parking a car to signal the remaining distance to its trunk.

Sound can also be sensed to be pleasant or unpleasant, which is called the hedonics of a sound. This relates to another property of sound, namely that it can produce an affect. A phenomenon experienced when emotional associations or meanings are conveyed along the sound (Cariani 2009).

⁵and therefore also tones

3.4.2 Basics of Wave Theory: Beat and Roughness

A closer look to the theory of sine waves, which are the basic components of all tones, explains the concept of beat and roughness.

In wave theory, a beat is the interference of two sine waves, which occurs when their frequencies are close together. The resulting wave gains a beating characteristic due to the amplitude which varies with the beat-frequency. This beat-frequency can be calculated to be the difference of the two initial frequencies. The pitch frequency of the resulting wave accords to the mean of the two initial frequencies. If the frequencies are a bit further apart, the beat-frequency gets too high to be resolved by the human ear. As a consequence, roughness within the tone is experienced. In that case the tone loses its beating characteristic and is perceived as constant in time. When the two frequencies are put even further apart, then they are perceived as two distinct, hence non interfering, tones (Fastl 2007, Cariani 2009).

In Figure 3.6 the amount of roughness which is perceived by two tones at different intervals is to be seen⁶. The amount of roughness is plotted against the frequency interval. It shows the beating characteristic in the first part, where the roughness is already increasing rapidly. Then, at the maximum of the roughness, the beat-frequency has become too high to be resolved. With decreasing roughness it is steadily becoming easier to perceive the sound as two distinct tones (Cariani 2009).

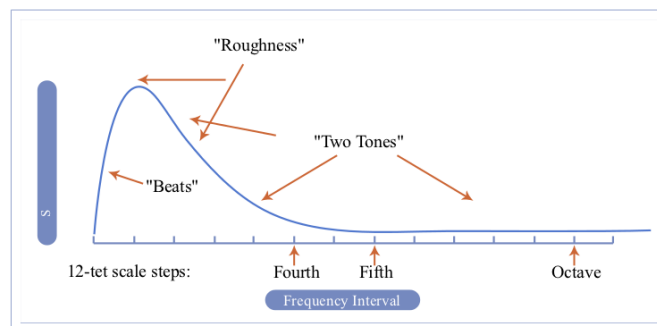


Figure 3.6: Amount of Roughness plotted against the Frequency Interval (Cariani 2009)

3.4.3 Music Theory: Consonance, Dissonance and Octave

The basic concept of consonance and dissonance is described by the overall roughness which is generated by superimposing tones. Two tones played together overlay in their spectrum and the resulting roughness has to be analyzed in each case two frequencies are so close as to produce roughness.

⁶With “S” standing for “Sensory Dissonance”, which is equivalent to roughness.

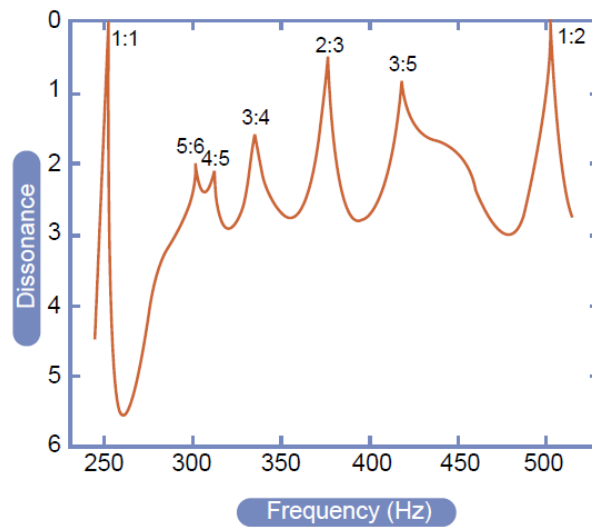


Figure 3.7: Relative Dissonance of harmonic Tones dependent on the Interval (Cariani 2009)

Considering harmonic tones, there is a clear characteristic of which frequencies are mainly present in addition to the pitch frequency. This makes it possible to calculate the overall roughness and therefore the dissonance. In Figure 3.7 the roughness of all the interfering frequencies is added up and displayed as a function of the interval between the two tones. The maxima are the intervals, which have the least roughness and therefore are the consonant ratios of two harmonic tones played together (Fastl 2007, Cariani 2009).

Methods used to study the Perception of a Sound

The methods used to study the perception of sound are exactly the same as in measuring every other sensory experience. Specifically those are psychophysical methods of threshold detection, determining the just noticeable difference, calculating Weber Fractions and presenting Two-Alternative Forced-Choice tasks. All of which will be employed in the experiments explicated in the later chapters.

4 Methodology

4.1 Psychophysical Methods

The beginning of psychophysical investigations was marked by German physiologist Ernst Heinrich Weber's (1795–1878) threshold experiments in which he studied the response to two physical stimuli differing in magnitude. In 1860 the German scientist Gustav Theodor Fechner (1801–1887) presented his ideas about the relationship between body and mind in his book “Elemente der Psychophysik” and contributed to Weber's thoughts by writing out the equation which can be seen in Figure 4.1 (Ross 1996). Fechner adopted Weber's theories and results, expanded them and eventually mathematically integrated them to form the Weber-Fechner law (Allesch 1987).

$$\frac{\Delta\varphi}{\varphi} = c \text{ or } \Delta\varphi = c \cdot \varphi$$

Figure 4.1: Weber-Fechner Law

This law constitutes that the relative difference, in other words, the threshold from which on a modified stimulus ($\Delta\varphi$) that can be distinguished from the noise or stimulus (φ), would be constant (c) for every sensory modality. They all obey the Weber-Fechner Law even though they possess different Weber Fractions. The proportion of the stimulus values remains constant, while the absolute data differs. The Weber-Fechner Law equation is expressed as follows: $\Delta\varphi$ is the increase in stimulus intensity needed for stimulus φ to be just noticeable different from the previous one. The constant c will then be experimentally determined. Thus “the difference in magnitude necessary to discriminate between a reference stimulus and a second stimulus increases with the strength of the reference stimulus” (Kandel 2000:421). For example, a Weber Fraction of 0.01 denotes that the observer is able to reliably detect a change in stimulus intensity of 1%. The smaller the constant, the higher the resolution of the respective sensory function and the more likely small changes in stimulus intensity would be detected. However, there is the exception that the Weber Fraction does not hold true for perception at very high or very low intensities (Wieser 2009). Fechner illustrated it as follows:

“A coin in this sense is of much less worth for the rich than for the poor. And even if it makes a beggar happy for a day, it will go unnoticed as a gain to the fortune by a millionaire.” (Fechner 1860 I:235).

Even though his book along with the ideas of psychophysics came out a long time ago, psychophysics concerns itself with one of the fundamental and still ongoing inquiries of various disciplines featuring the goal to study the relation between the physical and phenomenal world, between stimuli and sensation. For psychologists, understanding sensation would be equalized with understanding the processes of the human mind. Therefore experimental psychology adopted the methodology of studying perception by designing adequate experiments and formulating models (Gescheider 1997). During Fechner's times no adequate physiological methods existed that would provide objective measurements of sensory or physiological functions. “Sensory physiology at that time was essentially

'subjective' in that it had to rely on subjective phenomena, that is, on percepts rather than on receptor potentials [...]" (Ehrenstein 1999:1211). Thus only the communicated relation between the purely physical, manipulable and quantitatively measurable stimulus and the subjective perception could become matter of the investigations using the stimulus as reference system (Wieser 2009).

A big improvement was made during the 1950s, by combining psychophysical methodology with statistical decision theory, which was consequentially labeled Signal Detection Theory (SDT) and is based on two processes: sensory perception and decision. "The sensory process transforms the physical stimulus energy into an internal representation and the decision process decides what response to make based on this internal representation" (Harvey 2003:3).

4.2 The Signal Detection Theory

Central to the Signal Detection Theory (SDT) is the determination of the sensory perception threshold for a stimulus. Sensory events need a threshold in order to be consciously perceived. This threshold is a subjective criterion set by each individual oneself and depends on whether the subject is a conservative responder, who needs to be very sure that a stimulus was perceived and generally prefers to say "no" when unsure, or a liberal one that responds with a "yes" whenever the possibility is given that the stimulus was presented and takes more risks. This difference in response criterion would cause the liberal threshold to appear lower than the conservative one, even though both responders might perceive the same, but answer according to a different state of mind. The Signal Detection Theory revokes this problem (Goldstein 2010).

As mentioned above, before the perception threshold is reached, it can be considered unconscious. Using psychophysics, Weber and Fechner came up with the concept of just noticeable difference, which is the weakest detectable sensation elicited by a stimulus (Gescheider 1997). A person's sensitivity to external stimuli is not constant and tends to fluctuate over each point in time. Therefore the detection is not a deterministic, but a probabilistic process and evaluation requires a lot of redundant trials at various signal strengths to receive a suitable estimate of the threshold. At the beginning, the signal strength will oscillate around the optimal value until it is adjusted by systematic adaptation. The threshold value of the stimulus is consequentially averaged to receive an apt estimation.

The minimal amount of stimulus strength necessary to lift a person's sensory perception over the threshold of consciousness is called absolute threshold. It is the intensity which the observer is just barely able to detect. If otherwise the result refers to the minimal intensity needed to produce a noticeable perceptual difference in sensory experience, then the detected level is called difference threshold. The modifiable comparison stimulus must therefore deviate from a constant background stimulus. The difference threshold always ranges on stimulus intensities above the absolute threshold (Ehrenstein 1999).

According to that, the "SDT separates response determinants into those that involve detection, and are presumably a function of physiological variables (sensitivity), from those that involve decision and reflect the subject's tendency to report that a given event

has occurred (response criterion) [...]” (Lloyd 1976:79).

An explanation of conditional probabilities can be seen in the payoff matrix in Table 1. If a signal is present and the observer responds with a “yes” it results in a hit. It would be a false alarm if the signal was actually absent but the observer still responded with a “yes”. A correct rejection occurs in the absence of a signal and the correct identification of it by the observer who responds with a “no”. However, if the signal was present and the response is “no”, it is a miss.

The payoff matrix is a simple detection paradigm providing four possible answers for the observer that measures the decision criterion and sensitivity. Sensitivity describes the percentage of correctly identified signal presentations (hit) against the percentage of incorrectly identified signal presentations (false alarms) (Goldstein 2010).

	“Yes”	“No”
Signal Present	Hit	Miss
Signal Absent	False Alarm	Correct Rejection

Table 1: Payoff Matrix

The detection and discrimination of perception thresholds has been applied in areas such as memory, vigilance, visual search, pain and sensory perception, as well as other fields that require estimations and discernments between stimuli.

4.3 The Two-Alternative Forced-Choice Task

Selecting one out of two given choices, even with limited information, is a common occurrence within many situations. The Two-Alternative Forced-Choice (TAFC) task represents a break down of complex problems into two alternatives. It is used to test response behaviour in humans and animals and is applied in the context of Signal Detection Theory (SDT) as assessment of a person’s response to the given stimuli, though this method is not limited to psychophysical assessment. Bogaz et al. stated that the TAFC task model “typically makes three assumptions: 1) evidence favoring each alternative is integrated over time, 2) the process is subject to random fluctuations, and 3) the decision is made when sufficient evidence has accumulated favoring one alternative over the other” (Bogacz 2006:701).

The TAFC task usually provides two forms of presentations: The alternative choices are presented simultaneously (e.g. visual stimuli such as pictures) or, specifically for the SDT, they are delayed by a time interval (e.g. tactile stimuli). After the presentation the respondent is asked for his preference of alternatives.

Though the name of the method indicates a forced choice, there is also the option of an unforced task, allowing the respondent to select an alternative “I do not know” (Kaernbach 2001).

5 Psychophysical Measurements

The first experiment employs the sensory substitution method of vibrotactile feedback. It is a preliminary study needed to assess the capability of the vibrotactile stimulation system and the threshold behaviour of the human tactile sense to perceive those stimulations. The goal of this study is to identify a maximum number of stimulation points within the range of the vibration motor, creating a two dimensional matrix of amplitude and frequency. The overall goal is to eventually integrate this vibrotactile stimulation system into a prosthesis to acquire closed loop control.

The mechanical stimulation system is able to generate complex tactile patterns by independently modulating amplitude and frequency of the vibration in the range of 0-12.6V and 10-250Hz. The psychophysical measurement assessed the threshold of the human tactile sense to perceive those tactile stimuli of different frequency and amplitude combinations. Subjects were tested in the style of a Signal Detection Theory paradigm by using a modified single-interval adjustment procedure to increase speed and objectivity. Subjects performed threshold discrimination tasks where either noise or signal plus noise was presented to them according to a predefined algorithm that tries to determine the next perception level at which the tactile difference is barely perceived. In the next step, the previously detected perception threshold will become the baseline background noise. In this sense, every next trial is based on the preceding (Ninu 2013).

In the end, a tactile matrix incorporating 15x27 distinct stimulation points, was deduced from the results of this study. It can be used to facilitate the application of haptic feedback for prosthetic devices (Ninu 2013).

5.1 Methodology

Four healthy participants that did without impairment of their sensory sensitivity were considered for this study. Moreover, to grant reproducibility, it has been assumed that sensory variability is lower among healthy persons than in amputees. Two females and two males between the age of 20 and 40 participated in the study of whom one subject had previous experience with psychometrical measurements. Test persons received instructions about their task and had the possibility to practice the procedure afterwards, questions could be asked at any time.

Signal Detection Theory

As explained in 4.1 Psychophysical Methodology, Signal Detection Theory provides an analyzing tool for decision making. The scenario for this experiment is staged as follows: There can either be a tactile stimulus or a change of it, which codes for "signal present"; or there is no tactile stimulus, which codes for "signal absent". According to the payoff matrix (Table 1), irrespectively if a tactile stimulus is present, the observer can respond with a "yes" or "no". The difference in this study to the classical SDT procedure is the fact, that the stimulus intensity is not always the same, but instead varies.

The signal is the tactile stimulus presented on the person's skin, while noise is every other stimulus in the environment. Because the tactile stimulus can sometimes be very faint, noise can be mistaken for the signal and can cause false alarms (Goldstein 2010).

Feeling a tactile sensation when there is none present is an example of tactile noise. In the SDT, trials are built like this: noise is always present and in some trials, a stimulus is added to the noise.

Method of Adjustment

An easy way to determine the absolute and difference thresholds is to adjust the stimulus intensity until it is just noticeable for the test subject. Usually, it is the observer who can regulate the stimulus intensity until it is just barely noticeable. But as this method is highly subjective, the observer was deprived of this ability. The method of adjustment is now a predetermined, automatic process - a series of increasing signal strength and decreasing signal strength alternating several times. In the end the result of every trial is averaged to obtain an estimate of the sought after threshold (Ehrenstein 1999).

Adaptive Testing

Adaptive testing is a procedure used to stay close to the threshold according to the subject's response in each trial. The applied stimuli fluctuate around the threshold area while adapting the sequence of presentations to finally narrow down on one value. This method is quite efficient because the range of stimulation keeps getting smaller and therefore most of the stimulus values are concentrated around the threshold. An application of adaptive testing is the staircase method (Ehrenstein 1999). It is illustrated in Figure 5.1. The staircase method is very straightforward, there is no need for many assumptions of the psychometric function or complicated computation. The stimulus presentation starts at one given value and the adaptive curve as seen in Figure 5.1 follows the rules of descending when the observer perceives a stimulus (the observer answers with "yes") and ascending if the stimulus is not perceived (answers with "no"). The stimulus intensity is reduced as long as the observer responds that the stimulus is perceived. When eventually the stimulus is regarded as too weak by the observer, the direction of presentation is reversed for the following presentation. The next trial placement is generated by using the previous responses within an adaptive track to select the next placement. In this way, the stimulus intensity is increased and decreased according to the observer's answers. Subsequently, a threshold estimate is provided by averaging the stimulus intensities at which the observer's response switched (Ehrenstein 1999).

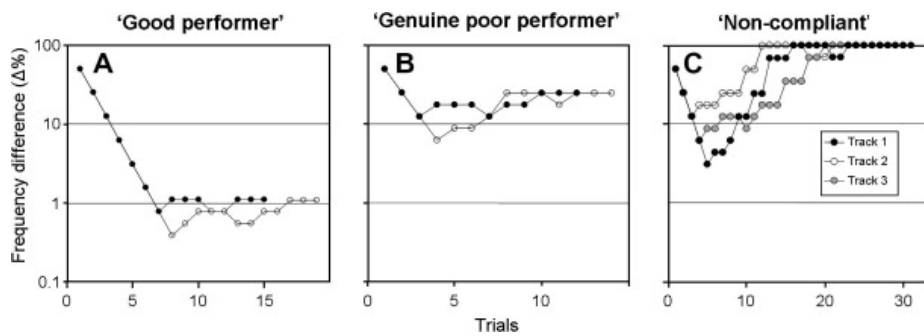


Figure 5.1: Staircase (Moore 2008:150)

The Single-Interval Adjustment-Matrix (SIAM) proposed by Kaernbach (2001) was

used in this study to determine a Just Noticeable Difference (JND). This procedure has been described as being unbiased and adaptive, and it also requires only half as many trials to achieve the same precision as the classical two-interval forced-choice method. For this psychometric evaluation the SIAM has been slightly modified in a sense, that the participant has to detect a change in signal value from the baseline instead of just noticing the presence or absence of a signal. Signal as well as baseline presentations are always followed by phase in which no stimulation occurs. However, such circumstances prevent the possibility of a direct comparison between baseline and signal levels. To accommodate this change between baseline and signal, the classical SIAM approach has been adapted (Ninu 2013).

Forced-Choice Task

Psychophysical methods rely on responses made by the subject on what sensory information was perceived. This approach was already introduced in chapter 4.3. In the classical method, the subject either responds with a “yes” if the stimulus was perceived or with a “no” if it was not. This approach is highly subjective, as the experiment conductor can not control if the report was correct or not. The Forced-Choice task provides a more objective approach, as the subject is required to give an affirmative response during every stimulus presentation during a certain time window. If the stimulus was perceived, subjects could respond with a “yes”. Should they fail to do so during certain amount of time, a time out occurred and the subjects were asked to affirm if they did not perceive the stimulus. However, if they did perceive it, and were just too slow to confirm the perception, repetition of the trial commenced.

The practice of forced-choice methods reveals that many subjects can discern stimuli so weak that they claim, they actually cannot feel them. Thus forced-choice “testing confirms that stimulus intensities can be discerned below the absolute thresholds defined by an unforced, more subjective procedure” (Ehrenstein 1999:1219).

5.2 Set Up

The experimental set-up consists of four basic elements: The control unit that embeds the psychophysical procedure, the motor generating the vibrations, the control panel with which the participant interacts (can be seen in Figure 5.2), and the PC that runs a software interface for supervision.



Figure 5.2: Set-Up Control Panel

The communication between the PC and the control unit is bidirectional. The PC defines and sends commands to the control unit which define the psychophysical procedure of its behaviour while in the opposite direction the progress of the psychophysical tracks will be transmitted to the PC for immediate supervision. Based on the subject's behaviour, the control unit generates stimulation commands that are further conveyed into physical tactile stimulation.

The vibration motor was placed at the right forearm near the elbow and participants let their arms rest on a table, so they were able to comfortably pull the levers while the motor was still kept away from the table to not induce unwanted, confounding vibration.

By pulling either the left or right trigger, participants are able to interact with the control panel. The right lever corresponds to "Yes, I have perceived a difference." and the left lever corresponds to "No, I have not perceived any difference.", either acknowledging the perception of the stimulus or acknowledging its miss. If the right lever is kept pulled, only the background noise will be presented, but no stimulus. This poses as an idle mode in case a participant cannot concentrate on the task due to disruptive background noise.

Two LEDs in green and red are installed as part of the control unit to provide immediate visual feedback to the participants. The green light represents a verification that occurs when a stimulus presentation was successfully identified by the subject by pulling the "yes" lever. The red light indicates a time out, which occurs when a stimulus was presented but not acknowledged by the subject. Because of the continuous visual feedback, participants will immediately know the accuracy of their choice and can keep their response criterion stable. Moreover, it acts as a motivational factor, an important consideration for an experiment that lasts above five hours.

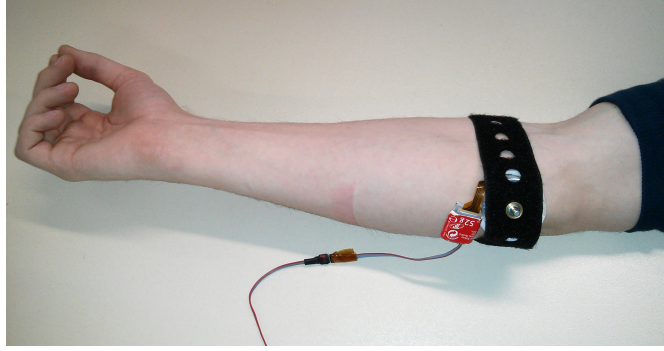


Figure 5.3: Motor Placement

5.2.1 The Vibration Motor

As introduced, the device used in the psychophysical evaluation is able to generate elaborate vibrotactile stimulation by independently modulating the frequency and amplitude of the vibration. The stimulation device is a brushless Maxon BLDC motor that due to its electronic rather than mechanical commutation has a higher life expectancy in settings when the motor has to continuously accelerate and decelerate to generate vibrations. With a height of 8mm and a diameter of 32mm, and supplied with 12.6V to achieve 6W of electrical power, the motor provides a feasible compromise between efficiency and size (Ninu 2013).

The magnetic field of the motor coils accelerates the rotor and the resulting inertial force drives the stator, which stimulates the skin. The rotor generates vibration and its magnitude of force is proportional to the motor acceleration. The stator circularly moves around the rotational axis of the rotor and thus stretches the skin tangentially. Tangential indentations have shown to be more efficient than normal indentations (Kaernbach 1990).

The vibrator's stimulation range encompasses frequencies from 10Hz to 250 Hz according to the thresholds of the vibration sensitive mechanoreceptors in the skin. The vibratory effect of the motor is caused by a continuous change in rotor direction. Varying the time in between two changes in direction modulates the frequency while the voltage applied to the motor modulates the amplitude.

The motor is cased by aluminum and kept into place onto the participants skin by a touch fastener band on the lower arm. To achieve a better fit for the application the standard Maxon motor has been slightly modified (Ninu 2013). It was placed on the participants' forearm near the elbow, as seen in Figure 5.3. The motor was attached to the skin by a strap and was preloaded with a force of approximately 2N.

The generated vibrations were measured by using a three axes accelerometer (MMA7368L) and signals were acquired with a 2 kHz sampling rate. The magnitude of the acceleration was determined as AC RMS of the module of the acceleration measured on every axis. AC RMS is the root mean square (RMS) value of the waveform minus the DC Average – equivalent to a ripple measurement (Ninu 2013).

5.3 Measurement Procedure

The goal of the measurements is to span a matrix of control points corresponding to the JNDs, the minimal change of stimulus frequency or amplitude with regard to a baseline

that can be sensed. A complete psychophysical characterization of such a matrix would require a large number of repetitive presentations. To reduce testing time but still keep a valid result, a reduced number of measurements was performed and the remaining points were estimated. The testing points of the matrix correspond to 20%, 40%, 60% and 80% of the maximum frequency and maximum amplitude, as both dimensions could be regulated independently. While one input (e.g. frequency) was held constant at either of those percentages, the other input (e.g. amplitude) was divided into ten equidistant steps (corresponding to 10%, 20%, 30%, ..., 100%). Those points also characterize the blank matrix and are called control points. Those control points are not permanent, but can be replaced by the actual stimulation points perceived by the subject. They represent a grid on which to orient the stimulation (see Figure 5.4).

The measurement procedure was executed as follows: First, one of the two conditions of constant amplitude or constant frequency was chosen. For every control point in the matrix of that condition, the corresponding stimulation points were determined - the detection threshold and the JNDs. In the constant frequency condition, frequency would not change, but the amplitude would. In ten steps from the detection threshold (0%) to the JNDs for the amplitude (10% to 100%). Each point was measured in increasing direction, from the baseline stimulation defined by the control point towards the maximum value of the tested input. A total of 80 values, 40 for constant frequency and 40 for constant amplitude, was concluded.

In the second step, Weber Fractions of the previously acquired JNDs were calculated to detect changes in the perceived intensity of the stimulus in regard to its magnitude.

Afterwards, a linear model was calculated to fit the Weber Fractions for both conditions of constant amplitude and constant frequency to obtain a continuous representation of Weber Fraction propagation.

Finally, the control points within the blank matrix were replaced by actual stimulation points spaced by the collected JNDs. The two axes correspond to the percentage of frequency and amplitude as well as JND steps for both conditions.

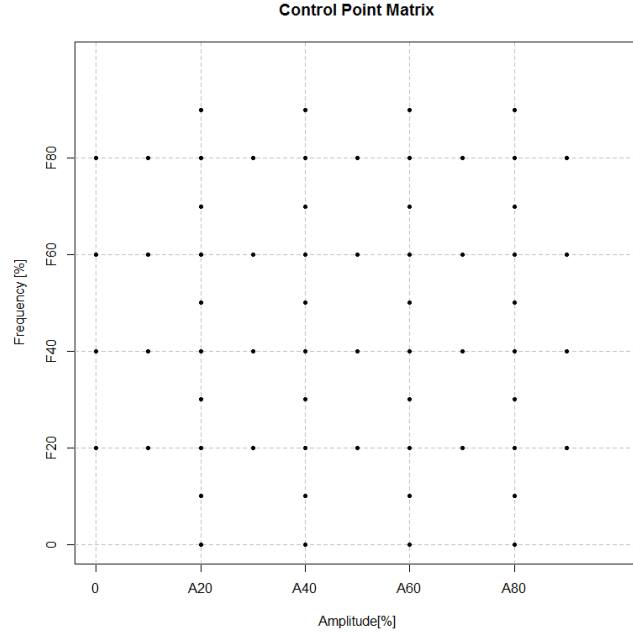


Figure 5.4: Control Point Matrix (Ninu 2013)

5.4 Analysis and Results

The psychometric evaluation was performed to obtain the Just Noticeable Differences (JNDs) and Weber Fractions of all thresholds as a mean to objectively assess the properties of this stimulation method. In these measurements, every JND corresponds to one point in the control point matrix, seen in Figure 5.4, in order to cover the full range of amplitude and frequency.

The first step in the analysis is to determine the JNDs. Figure 5.5 displays an exemplary threshold detection taken from the data set at the control point of 20% frequency and 0% amplitude (see Figure 5.4 for control points). The three tracks necessary to estimate the threshold value can be seen in different colors: The first track is colored black and starts 10% of the stimulation range (6000) and the step size is set to 5% (3000). The subsequent second track is based on the first, as it takes the averaged threshold value derived from track one. The step size of this track is congruent with the standard deviation acquired from the first track. The green colored track was the last one, which started at the threshold estimation of the precedent red track. As can be seen, each track demanded a different number of trials. A small number of trials stands for a clear distinction in perception, whereas a large number denotes an insecurity in perception. The JND is consequently calculated over all three threshold estimations. This detection and calculation process was repeated for all remaining JNDs of the control points in the matrix.

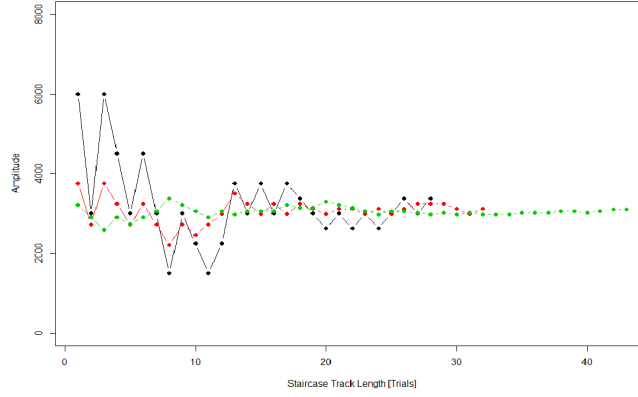


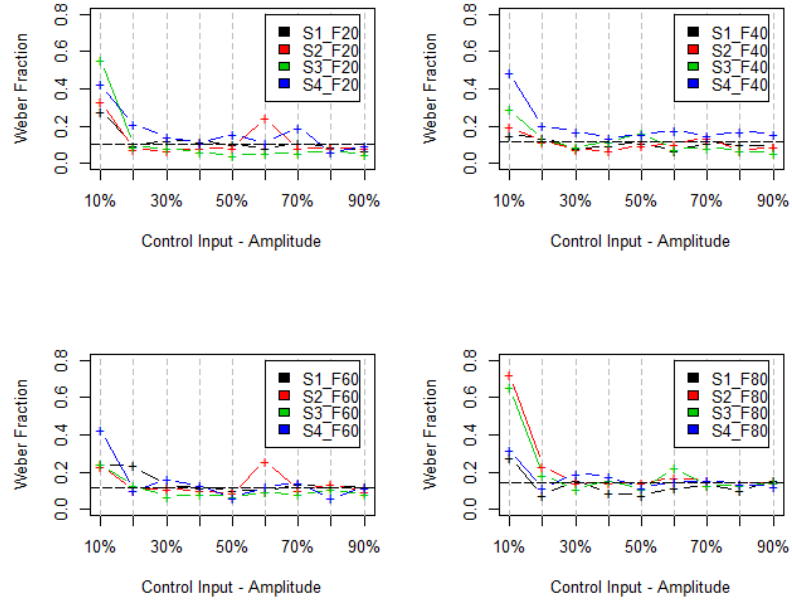
Figure 5.5: Threshold Detection (Ninu 2013)

The second step in analyzing the psychophysical measurements is to determine the Weber Fraction of the discrimination thresholds for every control point. The Weber Fraction refers to chapter 4.2, in which the Weber-Fechner Law was already mentioned. The ratio of $\Delta\varphi$ to φ is known as the Weber Fraction (Figure 5.6). In this analysis, it is calculated as the ratio between the discrimination JND and the absolute value of noise. Because division by zero is not valid, this ratio is not applied to detection thresholds as their noise level is zero.

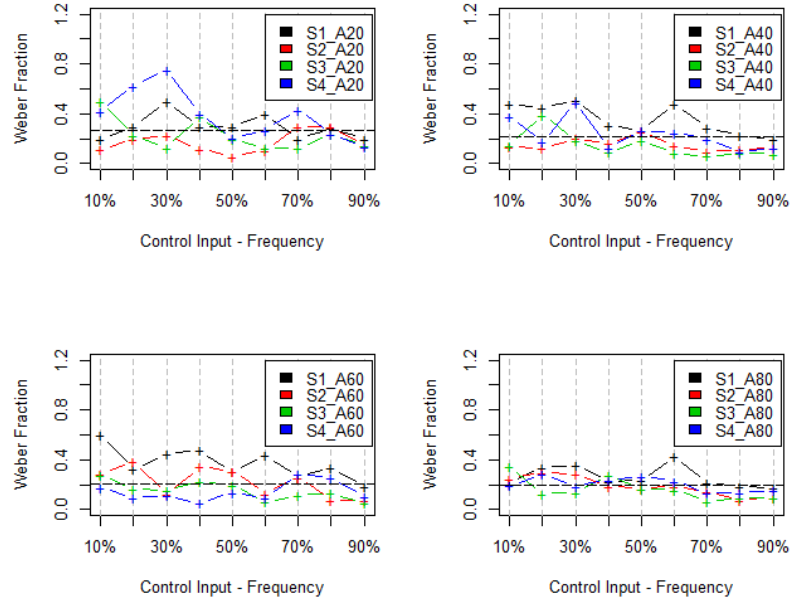
$$\frac{\Delta\varphi}{\varphi} = WF$$

Figure 5.6: Weber Fraction (WF)

All Weber Fractions were plotted separately, but pooled by two conditions: constant amplitude and constant frequency. The Weber Fractions characterize the perception of tactile stimuli in both constant amplitude and constant frequency stimulation. In Figure 5.7 the different Weber Fractions can be seen. The colored lines represent Weber Fractions obtained from four subjects. Amplitude and frequency were kept constant at 20%, 40%, 60% and 80% in their respective condition, which accounts for four lines per person. Thus in every diagram, 4 lines can be seen, whereas a single line of them represents one subject (S1 to S4) at one constant condition (F20 to F80 for constant frequency and A20 to A80 for constant amplitude). The Weber Fractions were determined at every control point in the matrix corresponding to 10-90% of the stimulation range seen at the bottom axis. The average trend is calculated as an overall mean and plotted as a black dashed line.



(a) Constant Frequency



(b) Constant Amplitude

Figure 5.7: Conditions (Ninu 2013)

In Figure 5.7a, showing the constant frequency condition, it can be seen that inter and intra subject variability is low and distribution homogenous. Only for the first step of 10% of input change, there is a significant difference in contrast to the other steps. However, Weber Fractions for small baseline values are less stable due to a division by a smaller number, and thus the first step was not considered when fitting the linear model.

In Figure 5.7b, showing the constant amplitude condition, variability is much higher than in the constant frequency condition. A decrease in variability seems to occur towards the end of the plotted lines, with increasing magnitude of the input. Weber Fractions for the 80% constant amplitude condition also seem to be more homogenous in general. No clear trend according to every step in the input change from 10% to 90% can be observed though.

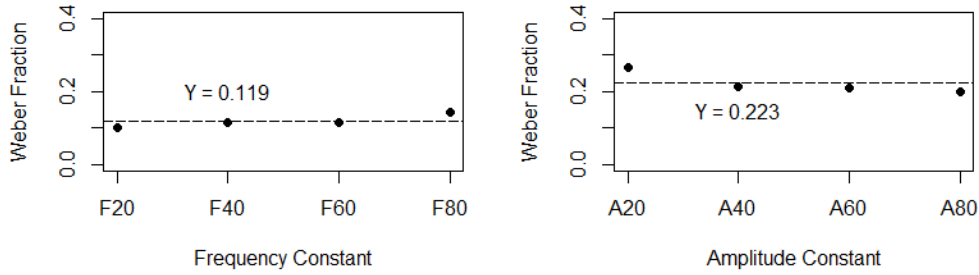


Figure 5.8: Average Weber Fraction

This is illustrated more concisely in Figure 5.8, where the average Weber Fractions of both constant conditions can be seen by a black dashed line. The results of Figure 5.7a and Figure 5.7b were summarized by an overall mean and standard deviation and plotted into two graphs. In the constant frequency condition, a slight increase in mean value can be seen from F20 to F80. Whereas for the constant amplitude condition, an opposite trend can be observed. However, the differences are too small to be statistically relevant. In the end, a constant value for every condition, representing the final Weber Fraction was determined ($\frac{WF_A}{WF_F}$). Figure 5.9 explains the method to derive the final vibel matrix. F_i and A_i stand for the control point frequency and amplitude respectively, $JND_{F_i}(A_i)$ and $JND_{A_i}(F_i)$ stand for amplitude with frequency set to F_i (constant frequency condition) and JND for frequency with amplitude set to A_i (constant amplitude condition). $WF_{F_i}(A_i)$ and $WF_{A_i}(F_i)$ denote the Weber Fractions with amplitude and frequency set to F_i and A_i respectively.

Firstly, JNDs in the control points were determined for the constant frequency (on the left) and constant amplitude (on the right) conditions by using the SIAM method. Subsequent corresponding Weber Fractions were calculated and fitted to a linear model to gain a continuous representation. The now estimated collection of JND steps along the amplitude and frequency axes were projected onto a plane, resulting in a vibel matrix of correlating steps. Finally, this resulted in 15 JND steps along the frequency axis and 27 JND steps along the amplitude axis. The JNDs extend along with the increase in stimulation parameters from left to right along abscissa, and from bottom up along the ordinate.

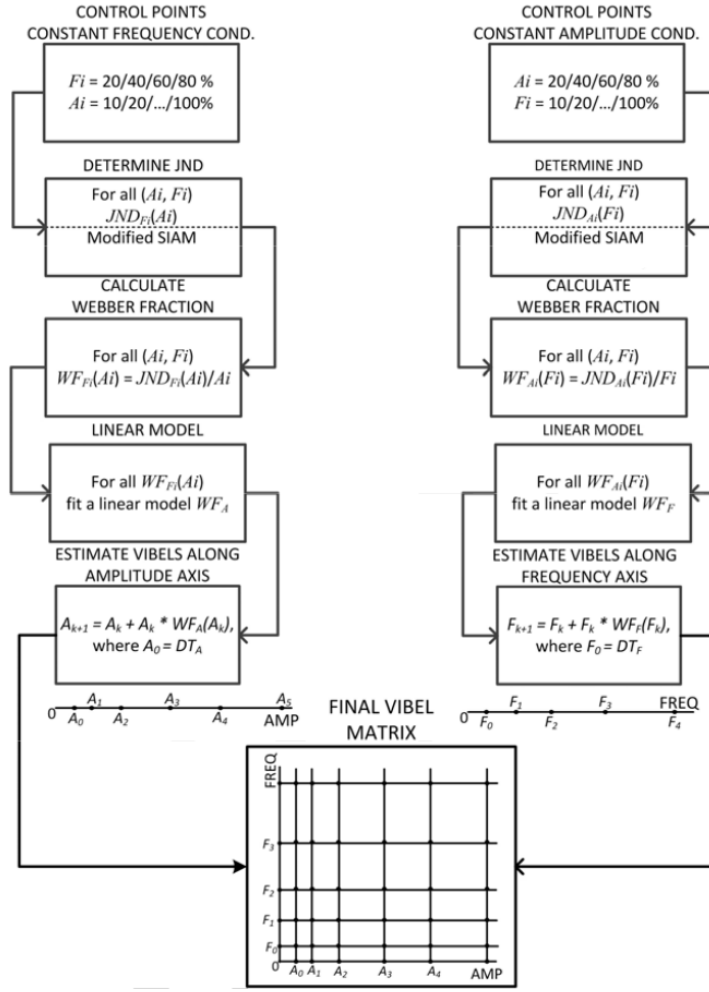


Figure 5.9: Summary of Vibrel Matrix Generation (Ninu 2013)

In Figure 5.10 the resulting matrix of vibels describing the space of the perceived stimulation can be seen. It defines the psychophysical characteristics of the vibratory stimulation for the motor used in the these experiments. The method to derive this matrix is explained in Figure 5.9 and the recursive equations to generate the JNDs along the stimulation parameter axes can be seen in Figure 5.11.

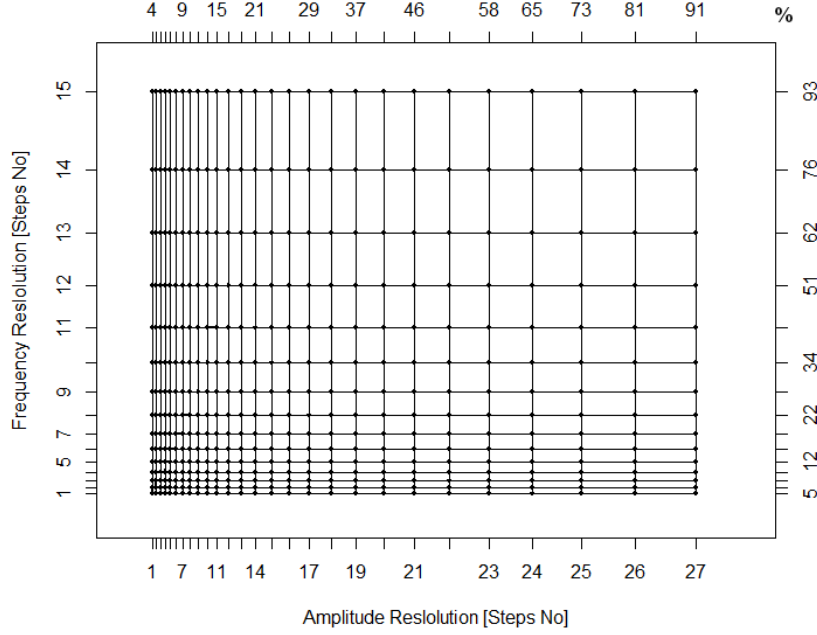


Figure 5.10: Vibrel Matrix (Ninu 2013)

$$\begin{aligned} A_{k+1} &= A_k (1 + W F_A) \\ F_{k+1} &= F_k (1 + W F_F) \end{aligned}$$

Figure 5.11: Linear Model

5.5 Summary and Discussion

The goal of this study was to create a complete model of perceived stimulation points accommodated within the stimulation range, and not only receiving acknowledgment from the subjects that a vibration was perceived on some values of frequency and amplitude. Having a complete reference facilitates information transfer between sensor and human, exploiting the full capability of the stimulation device to induce haptic sensations to the amputees. Another advantage of this model is the possibility to compare other stimulation technologies which employ similar or different modalities.

Psychophysical assessments have been performed to characterize the novel vibratory stimulation technique on the basis of the human perception levels. The subject's capability was evaluated in regard to detection and discrimination of tactile stimuli that were varied in amplitude and frequency. To derive sensitivity, the Just Noticeable Difference was calculated as the size of difference between two adjacent stimuli that are just able to be told apart. The two stimulation parameters⁷ could be modulated independently as well as simultaneously. It is important to note here, that the amplitude is regulated as true degree of freedom without using several motors and without full motor rotations as done by Cipriani et al. (2012). The vibration technique is implemented in a simple but efficient way: a standard electric motor is strapped onto the skin and the methodology

⁷amplitude and frequency

is very flexible. However, the gain in flexibility of this stimulation method comes at the expense of larger geometry and energy expenditure.

A matrix of vibels displaying a resolution of 15×27 in frequency and amplitude space was generated according to the results of the psychophysical evaluation, which count for 15×27 independently discriminable haptic points. Psychophysical measurements are inherently subjective and can exhibit a large variability, which was reflected in the measurements. Variability occurs due to various external and internal factors, such as body posture, skin condition, mood, attention and motion artefacts. To obtain a valid estimate of the mean response of tested participants, a large quantity of trials was needed, after which the results were averaged across subjects as well as conditions. To decrease the time needed to perform those assessments, only a certain number of points within the control point matrix have been sampled. Afterwards, missing values were interpolated to gain a full set of sequential JND steps along both axes of the vibel matrix. The matrix can be seen as a guideline for the application of haptic feedback. Taking the information present within the matrix, vibrotactile patterns can be generated by changing the amplitude and frequency in between these steps. By adapting a stimulation signal, such as a pattern, according to those amplitude and frequency steps, the likelihood for a subject to detect a change within stimulus presentation is highly increased, since the matrix is build upon the subjects' average perception. Mapping the sensorial information from a prosthesis onto haptic patterns by using this vibel matrix allows for efficient information transfer between the prosthetic device and the human skin. Moreover, the matrix can be personalized by using the true values of a subject's performance. As of now, the results were averaged, but without doing so and instead using the subject specific Weber Fractions a personal vibel matrix can be constructed. This matrix however, would not display a uniformly distributed appearance, but would better represent the instantaneous structure of the perceived stimulation.

For both, constant amplitude or frequency conditions, there was no clear trend between individual outcomes. That accounts for the varying sensitivity among different subjects. However, there was a clear trend to be seen in the mean over the entire data set. Taking these findings into consideration, there must not necessarily be an assessment over all four constant amplitude and frequency conditions, but only for certain relevant control points. By adapting this procedure in the mentioned way, evaluation would become faster and thus a larger population could be tested. Moreover, the results would gain a generalizing character.

At last, the present form of the introduced methodology is still limited. The model is constructed based on detection thresholds determined for every control point within the control matrix, but only so in an increasing direction of stimulation from 0% to 100% on the amplitude and frequency axes. This distribution can be expanded to also contain the JNDs in a decreasing direction. Although, due to a masking effect, which will reduce the stimulus perception through an overlay of stimuli, the resulting JNDs are assumed to be larger than those of an increasing direction.

6 Pattern Generation and Evaluation

In this experiment, vibrotactile feedback patterns were generated and evaluated using a motor attached to the skin of healthy participants. It employed vibrations within a setting defined by the previous experiment. Three types of patterns were adopted which differed in amplitude and frequency combinations. Those patterns were subsequently evaluated for intuitiveness and preference according to prosthetic movements. The goal of this study was to create a pattern catalog in which one pattern codes for one movement and vice versa.

In previous chapters, the background for generating patterns as well as the integration of those other disciplines has been explained, as they should not just represent various random patterns without theoretical basis and meaning. The underlying idea was to model an intuitive sound to transfer a characteristic sound to other media.

This experiment serves to assess the capability of able-bodied participants to evaluate 20 different vibration patterns. The movements which were to be coded by patterns were inspired by Sören Lewis’ survey about user demands for sensory feedback (Lewis 2012). Four paired movements (thus eight in total) were to be coded with vibration patterns. Furthermore, the movements can be divided into four dynamic and four static ones. These movements are:

$$\begin{array}{l} \text{dynamic movements} \left\{ \begin{array}{l} 1) \text{ Hand Opening – Hand Closing} \\ 2) \text{ Grip Force Increase – Grip Force Decrease} \end{array} \right. \\ \text{static movements} \left\{ \begin{array}{l} 1) \text{ Hand Opened – Hand Closed} \\ 2) \text{ First Contact with Object – End of Contact with Object} \end{array} \right. \end{array}$$

In an application, feedback would only be provided when the prosthesis moves or an internal sensor is activated (e.g. a pressure sensor), because change is an very important information for the brain whereas a constant condition can be confidently blinded out (Pearson 2010). Thus, for example, an increase in grip force elicits a vibration, but when it remains immobile while the prosthesis grabs around an object, there is no vibrotactile feedback send back to the user. Feedback reappears when the prosthesis moves again, such as for decreasing the grip force and opening the hand. For when the hand is opening again, information about position and speed would be fed back again, and only when that state of “hand fully opened” is reached a short vibratory cue is given. If the hand stays in that position, no further vibratory information would be given, not until the prosthetic hand would start to change its position again.

6.1 Integration of Psychoacoustics

Psychoacoustics has already been introduced in chapter 3.4. The basic idea of integrating psychoacoustics into the generation of vibratory patterns is to transfer concepts of music theory to the area of haptics and tactile systems. This could offer the possibility to create interesting sensations on the skin. Properties to use in the creation of haptic feedback are for example, consonance and dissonance, rhythm and beat, as well as mnemonics and

cognitive associations.

The production of the tones is very important. In order to predict, if tones played together are consonant or dissonant there needs to be a certain rule by which can be determined how much roughness is produced. The goal is to predict the roughness of a given set of vibrations induced to the skin. In order to calculate the roughness, the structure of the vibrations is important and thus the way, they are produced.

For harmonic tones it can easily be analyzed how much dissonance, hence overall roughness is produced, when two tones are played together. The spectrum of both tones is known, thus calculabe for both dominant frequencies, as well as the roughness they produce when combined. Unfortunately, a problem arises when considering the vibration through motors on skin. The resonating frequencies of the skin by applying vibration are depending on way too many parameters. For instance the tension of the skin shifts the resonance frequencies. This not only deems it impossible to predict the dominant frequencies in the spectrum, but they are also varying with time. It leads to an unpredictable and time varying dissonance for two vibrations induced to the skin. In addition, every person may have a different “tonal skin system”. As a result it is impossible to use the concepts of consonance and dissonance with vibration motors applied on the skin. As such, sophisticated melodies with consonant and dissonant tonal intervals cannot be used as inspiration for generating patterns.

However, there are still other options available for what aspects of music theory to incorporate using a vibration motor. With two frequencies, there are beat and roughness phenomena which were already discussed in 3.4.2. Additionally, if the two motors have exactly the same frequency an no phase shift, they add up their amplitudes. The latter idea was considered in a study conducted by Cipriani et al. in 2012. They used imbalanced motors and thus had a dependence of frequency and amplitude. In order to use different amplitudes at one frequency they stacked together three motors of one kind. Furthermore, they had to run them all at exactly the same frequency, which was possible due to a stabilizing effect of the motors build in a stack, where the magnetic fields of the motors coupled. Cipriani et al. could apply three different amplitudes depending on the number of motors running. With this method they gained a considerable independence between frequency and amplitude. Also, they were able to use the beat phenomenon by placing the motors horizontally in a line. However, they did not further investigate the beat phenomenon in psychophysical regard. Lastly, together with the limited amplitude, a huge disadvantage of this technique is the long rise time of the signal of about 350-450ms (Cipriani 2012).

In summary it can be said that the remaining phenomena, that could be used, are beat and roughness. The motor used in the psychophysical experiments described in the previous chapter does not have a rise time. It is, moreover, possible to manipulate the amplitude in varying degrees with only one motor to induce beat, instead of two or three.

Roughness was of potential interest. Roughness is produced by choosing two frequencies close to one another, but not as closely as for creating beat. But since the vibration motor we used in the previous study is independently regulable for amplitude and frequency, there was no need to employ the two motors for producing roughness, as there were easier possibilities to simulate similar sensations.

Another important aspect are the mnemonics and cognitive associations with a tone or a beat, since life is filled with it. Mnemonics are a fundamental method especially in regard to learning and feedback. This already relates to intuitiveness, as the objective was to model a characteristic sound onto another medium. For example the sound of a beeper in a car that signals the distance to the adjacent car while parking. Familiar sounds, beats, tones and rhythms should establish an intuitive connection to objects that are touched by the prosthesis. Furthermore it should facilitate prosthetic control and promote embodiment.

6.2 Integration of Intuitiveness

As exposed in chapter 3.3.1, intuitiveness is an automatic, unconscious process based on familiarity and embodiment, which resorts to previously acquired knowledge to perceive and act on the environment. In the introductory phase of the following experiment, subjects were asked to get familiar with the prosthesis whose pictures were used within the experiment's interface. The intention was for them to get a grasp of what it feels and looks like to control a prosthesis, how its movements look like and how they are executed. During the experiment, subjects often gazed at their hand and performed the proposed movement on screen or looked at the prosthesis again, suggesting an immersion of the prosthetic movement according to the physiological movements.

While vibratory patterns or cues were applied as feedback during the experiment, subjects had no difficulty in assigning patterns to movements and verbalized their thoughts on it. All subjects reported the same pattern modality preference for certain movements, as can be seen as well in the quantitative statistical analysis in chapter 6.5.

Intuitiveness was investigated by splitting the participants into two groups, one naive group that received just the basic explanations and the interface introduction, without presenting and commenting on different pattern types. The performance in both groups was quantified to analyze statistical differences and commonalities. Feedback patterns should be intuitive enough, that movement and pattern mapping would accord in both groups. The mostly subtle vibratory patterns should relate to a previously acquired knowledge to create an intuitive feeling of movement. Intuition would take place as a response to those vibration patterns. Even though in this experiment, not all vibratory cues were regarded as subtle by the participants, the aim is to design the patterns as subtle as possible, so that it would normally be ignored as background noise, but still be perceivable enough to act on them.

6.3 Pattern Generation

Based on the results obtained from the psychometric measurements and shown in the vibel matrix, 20 patterns have been generated. Those patterns take into consideration the derived frequency, amplitude and difference in them the test persons could perceive best. Thus a sector enclosing the highest resolution was chosen, which resulted in a maximum amplitude used for generating the patterns of 21% corresponding to 2,65V and maximum frequency of 24% corresponding to 60Hz. To adhere to the resolution of the vibel matrix, the amplitude range was split into 15 steps, that encompassed 21% of

the highest resolution within the matrix, and the frequency range into seven steps, that represent 24% in the matrix. The selected sector is depicted in Figure 6.1. Although, to also incorporate the phenomena, that with increasing frequency the amplitude appears to rise as well, a higher frequency of 30% corresponding to 75Hz just outside the resolution sector has also been considered as well.

Those parameters were further combined with each other to generate 20 meaningful vibration patterns while keeping suggestions from other disciplines in mind. Combinations always follow the structure of one out of 15 steps of amplitude associated with one of the seven frequency steps for at least one and maximum nine combinations per pattern.

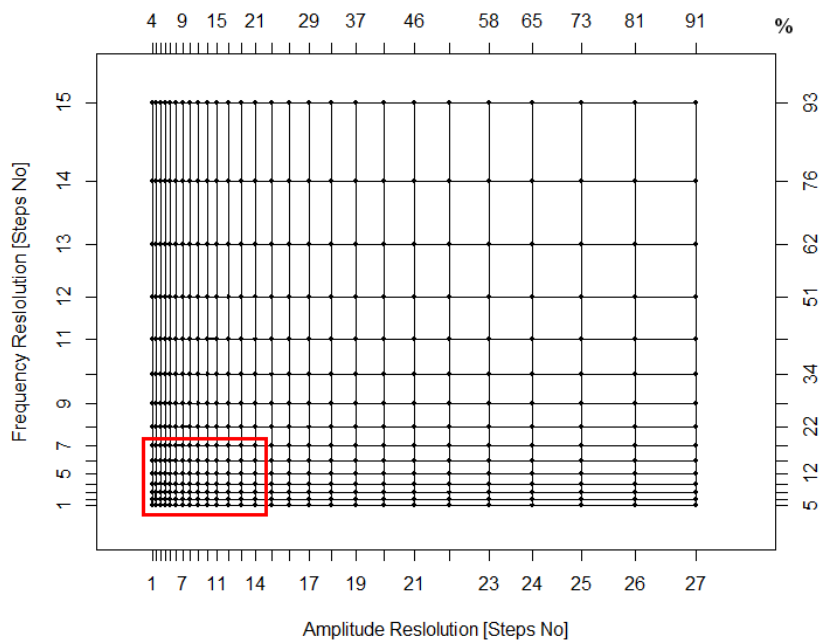


Figure 6.1: Chosen Sector from the Vibel Matrix

Essentially, three types of patterns were adopted: static, dynamic and pulse. The static pattern consisted of one or two amplitude and frequency combinations only, which moreover resulted in reducing the length of the pattern overall. The dynamic pattern consisted of at least three and maximum nine combinations and length of the pattern was prolonged by nature and by purposely extending the presentation time and break times, altering thus the nature of the pattern in different ways. The last pattern, which is a synthesis of a dynamic and a static pattern, shows features of a static one by embedding just one or two amplitude and frequency combinations, but arranging them in repeating order and thus extending the presentation time of the pattern to that of a dynamic one. The resulting arrangement is a pulsating pattern. The different pattern compositions can be seen from Figure 6.2 to Figure 6.11. Out of the 20 patterns, there were 9 dynamic ones, 6 static patterns and 5 pulsed patterns.

Pattern arrangement included increasing and decreasing amplitude and frequency as well as alternating between them and keeping them constant. Break time in between

one amplitude and frequency composition was also varied, so that even with the same combinations, different patterns could be composed.

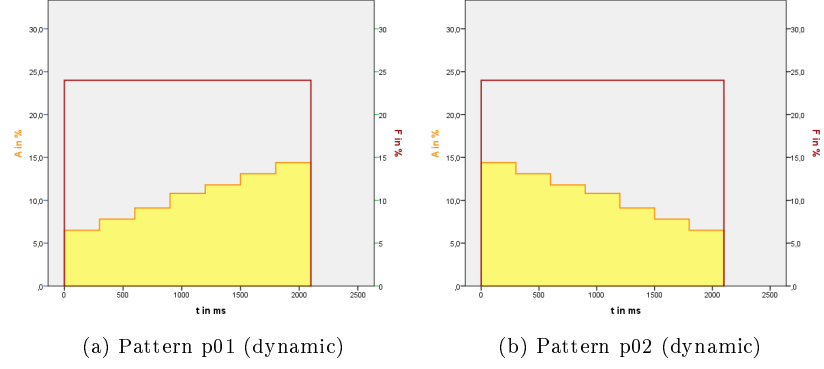


Figure 6.2: Pattern p01 and p02

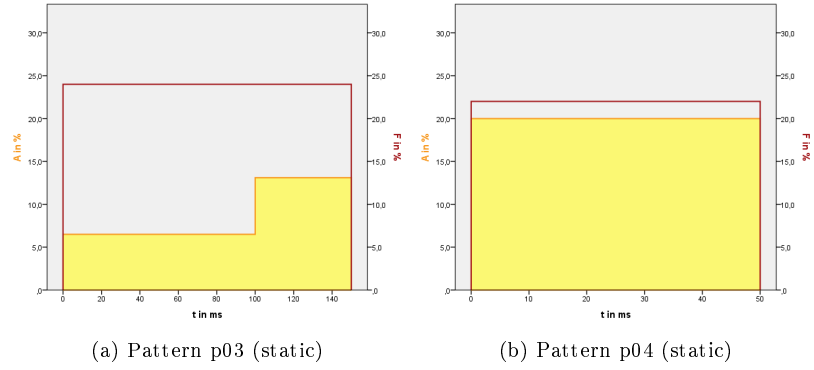


Figure 6.3: Pattern p03 and p04

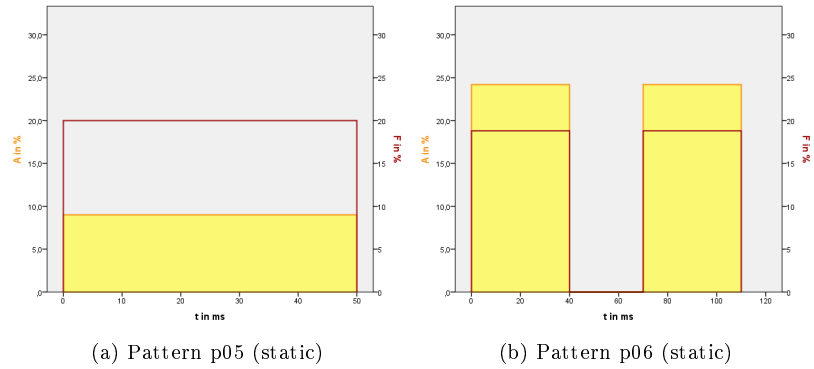


Figure 6.4: Pattern p05 and p06

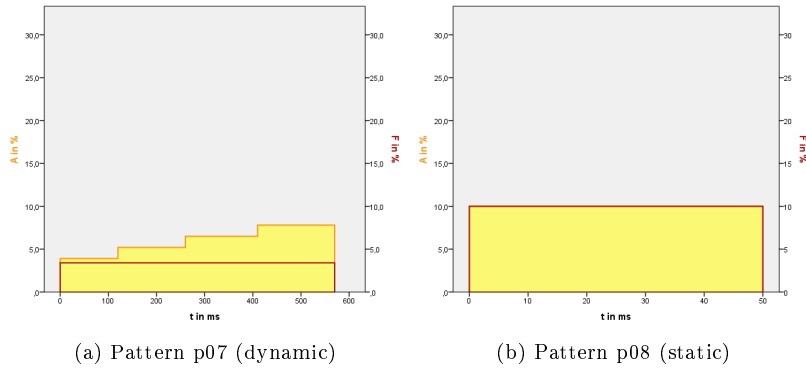


Figure 6.5: Pattern p07 and p08

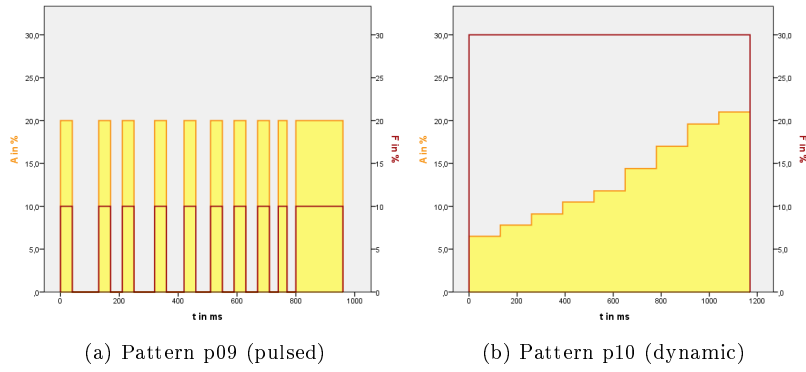


Figure 6.6: Pattern p09 and p10

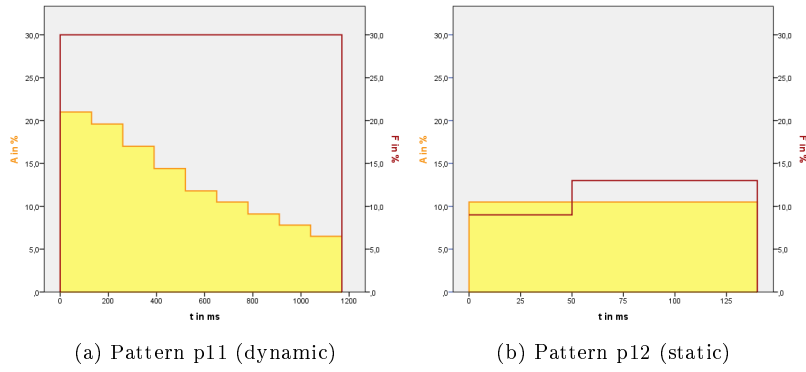


Figure 6.7: Pattern p11 and p12

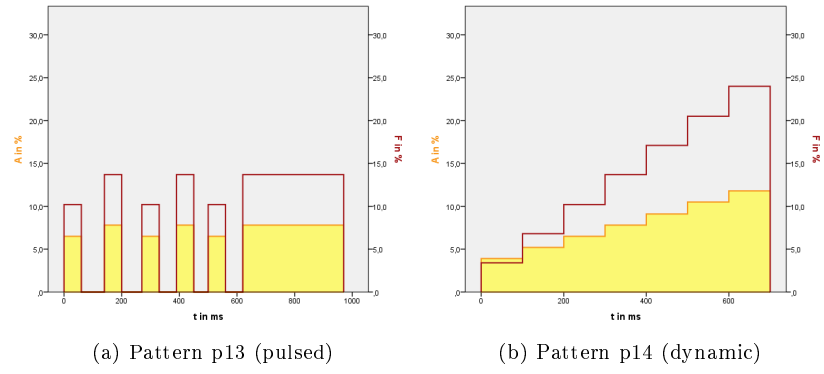


Figure 6.8: Pattern p13 and p14

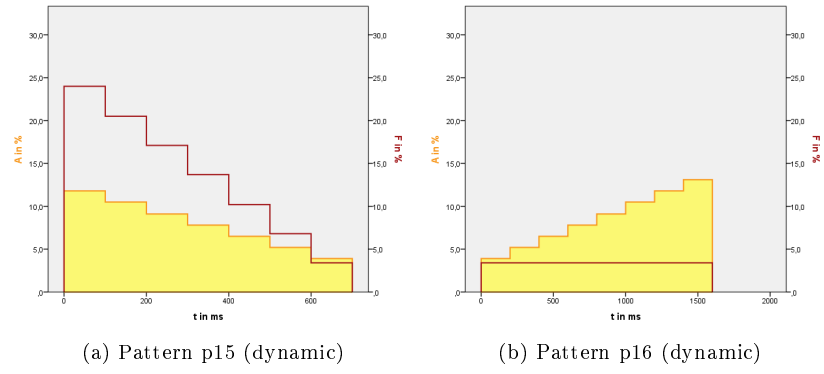


Figure 6.9: Pattern p15 and p16

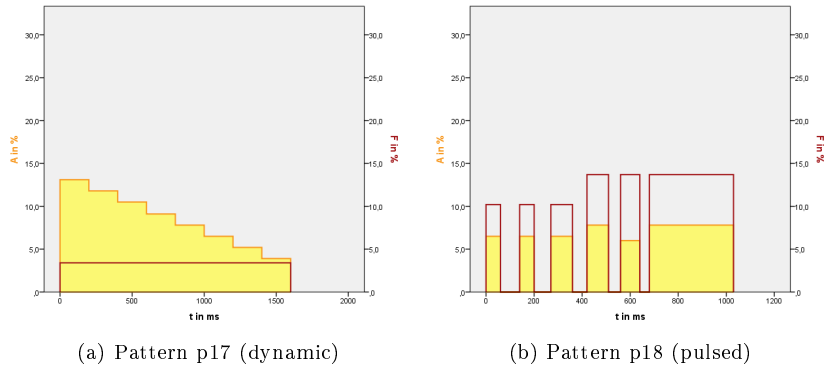


Figure 6.10: Pattern p17 and p18

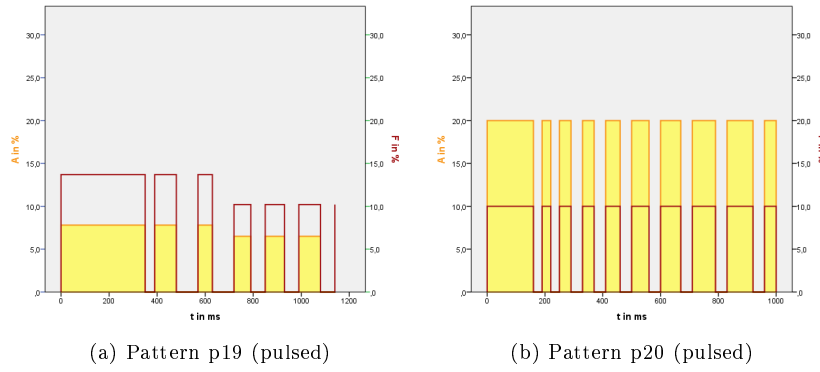


Figure 6.11: Pattern p19 and p20

6.4 Pattern Evaluation

6.4.1 Set-Up

The 15 subjects (aged 20 to 50, 3 female and 12 male) would face a table with the Michelangelo prosthesis from Otto Bock. They were instructed to accommodate themselves with the prosthesis by opening and closing it, squeezing a soft ball and look at the behaviour of it when the prosthetic hand is fully closed or opened. Movements were executed using a small joystick. This introductory phase lasted between 5 and 15 minutes and was necessary as the subjects should get a feeling for the way the prosthesis moves and to promote immersion. They should try out all the movements that were to come up in the subsequent experiment, where they should think about how the prosthesis would behave.

After that initialization phase, the actual experiment began. Instructions guiding through the experiment at all time were shown on a computer screen and a mouse was available for input. A wristband containing the vibration motor was attached to their forearm near the elbow that transmitted the vibrotactile patterns. The patterns were chosen randomly and played manually during the experiment by using the program shown in Figure 6.12. Subjects worked on their own to grant autonomy and to not make the subjects feel observed. Though the experimental conductor was next to them to present the patterns. The experiment consisted of 56 trials and lasted about 40 to 60 minutes in total. The whole experiment was untimed, though. Before the experiment, subjects were allocated to be part of either a naive group, which received just basic instructions, or the control group that received extensive instructions about patterns and movements. The accommodation phase with the prosthesis took place in both groups though.

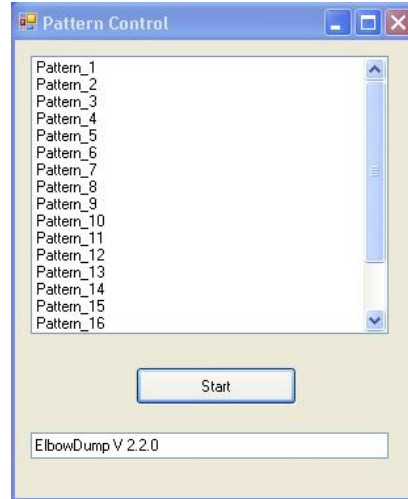


Figure 6.12: Pattern Control Window

6.4.2 Methodology

After the accommodation phase with the prosthesis, subjects were shown all the eight possible gestures that were to be coded during the experiment to provide a full picture, as seen in Figure 6.13. The gestures were divided into dynamic movements and static events. As described in the beginning of the chapter, the dynamic movements were divided into hand opening and hand closing, as well as grip force increase and grip force decrease. They describe a movement over time and were thus labeled dynamic. The static states are divided into hand opened and hand closed, and furthermore end of contact and first contact. It is important to stress the difference between a dynamic movement, that takes some time for the prosthesis to perform and the motionlessness of a state. The term “state” was introduced to further highlight the difference in gestures to the probands, even though the initial labeling was for eight movements.

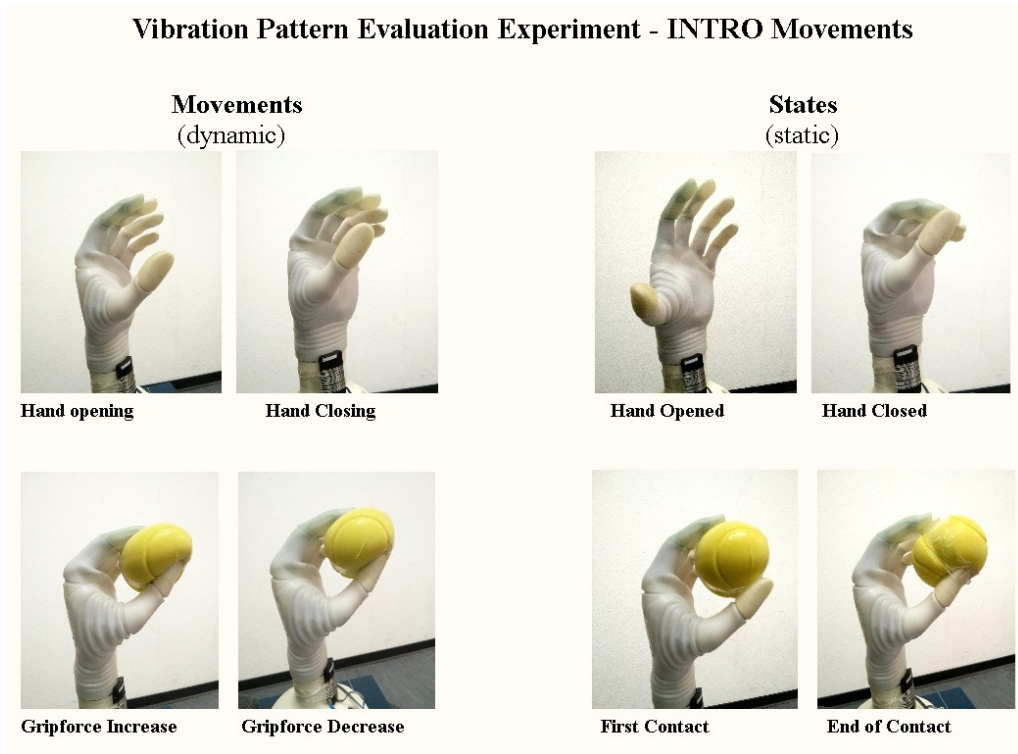


Figure 6.13: Prosthetic Movements

After explaining the possible images that turn up during the experiment, an exemplary trial was performed to acquaint the subjects with the experiment's interface. Figure 6.14 shows the screen the subjects see. Basically there are two things to do: 1) Choosing a matching image to the vibratory pattern, if there is, and 2) Rate it. The layout of the experiment was kept simple to not crowd the screen and let the subjects focus on their task. The actual trial and the total number of them were shown in the headline for the test persons information and motivation (12/56 in Figure 6.14).

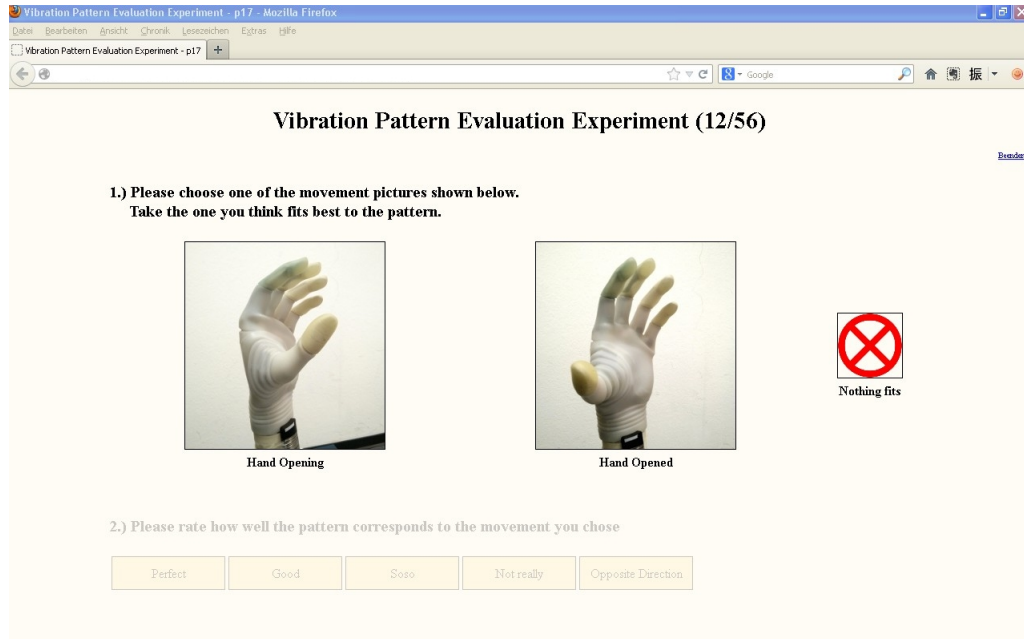


Figure 6.14: Introducing the Interface 1

On screen, the two images of each one of the eight movements in a distinctive phase were displayed. All pictures were presented randomly but equally distributed and no picture was paired with itself. The vibration patterns were also presented randomly and equally distributed: before one pattern would be presented a third time, all patterns had to be presented two times beforehand. Subjects were requested to choose one of the images according to which matches best to the applied vibration pattern they perceived on their arm: 1.) “Please choose one of the movement pictures shown below. Take the one you think fits best to the pattern.” If for the test persons a pattern does not fit any of the images, there is also the option of clicking the button for “Nothing fits”. This option is thought for a case, in which either the subject already has an idea for a movement and that movement’s picture is currently not presented, or if they cannot imagine any movement at all with that pattern. This corresponds to an unforced Two-Alternative Forced-Choice task, in which the possibility stands that the respondents in fact do know which images would fit best to the vibration, but none of those images are currently displayed on the screen.

Participants were instructed to choose the image (and the corresponding movement) that first comes to their mind. However, if there happened to be two similar images with conflicting interest, they were not forbidden to take their time either.

During the introductory phase, each type of pattern is played once to familiarize the test persons with the feedback method and the available pattern modalities.

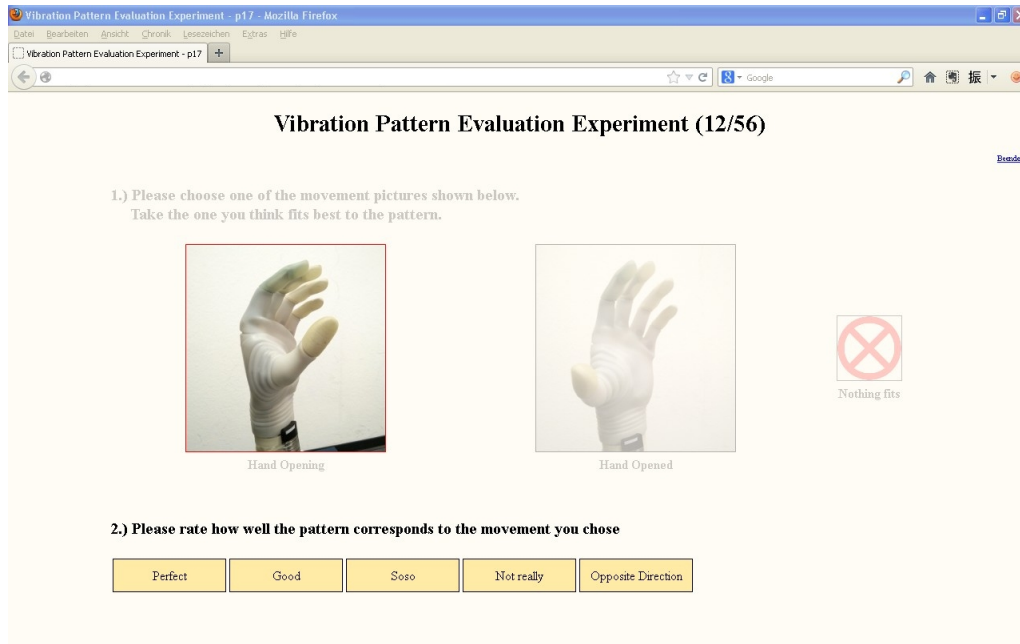


Figure 6.15: Introducing the Interface 2

After they voted for the image they think fits best, they are asked to rate it in an altered Two-Alternative Forced-Choice method, as seen in Figure 6.15: 2.) “Please rate how well the pattern corresponds to the movement you chose.” With the given options being “Perfect”, “Good”, “Soso”, “Not really” and “Opposite Direction”. While the first four options are rather self-explanatory, “Opposite Direction” stands for the option of choosing an image that is actually not given. This would be the case if the subject matches a pattern with, for example, Hand Opening. But in the picture set displayed on screen only the option Hand Closing is given. Now by pressing the “Opposite Direction” button, this pattern will be mapped to Hand Opening instead of the presented image for Hand Closing.

As patterns needed to be administered manually, and the test persons should not be aware which pattern was currently played to minimize intended answers, the demanded randomized pattern was shown in an unobtrusive fashion. It can be found in the window’s title, right after “Vibration Pattern Evaluation Experiment”. In the example of Figure 6.14 the requested pattern is p17.

A trial is finished as soon as the rating is placed. After 56 trials the experiment is over. A short qualitative interview took place right after finishing the last trial, assessing general sensation and perception of these patterns. This interview included questions about how comfortable having a vibrotactile feedback feels, if the feedback was too strong/too weak, or if that perception changed over time, if they had a specific movement in mind for a certain pattern, et cetera. Certainly, there was room for own comments, too.

6.5 Analysis and Results

Fifteen data sets accommodating 840 mappings of a certain pattern to a choice of two pre-given movements were analyzed using IBM SPSS Statistics 20 in German language.

Thus 840 patterns, 840 movements and the corresponding weighted rating and weighted total were evaluated. Weighted rating and weighted total was necessary as pattern types were not equally distributed within the set of 20 patterns (9 dynamic ones, 6 static ones and 5 pulsed ones). To achieve a meaningful distribution, the lowest common denominator was detected. Rating on the interface corresponds to rating in the analysis the following way:

"Perfect"	=	3 points
"Good"	=	2 points
"Soso"	=	1 point
"Not Really"	=	0 points
"Opposite Direction"	=	2 points

Table 2: Coded Rating

As a measure of intuitiveness, two groups were formed in order to compare the quantitative results. In the naive group, participants were neither extensively instructed about pattern modalities, nor were they shown all types during the interface introduction. Moreover, they were told about the possible movements which should be haptically coded, but were not shown a collage of them, as seen in Figure 6.13. The instructed group were shown the collage of the possible prosthetic movements and all pattern modalities during the introduction to the interface. Hence, instructions lasted longer, as the focus was not only to acquaint the participants with the interface, but also to provide them with an understanding of the pattern composition.

6.5.1 Distinct Groups: Naive and Instructed

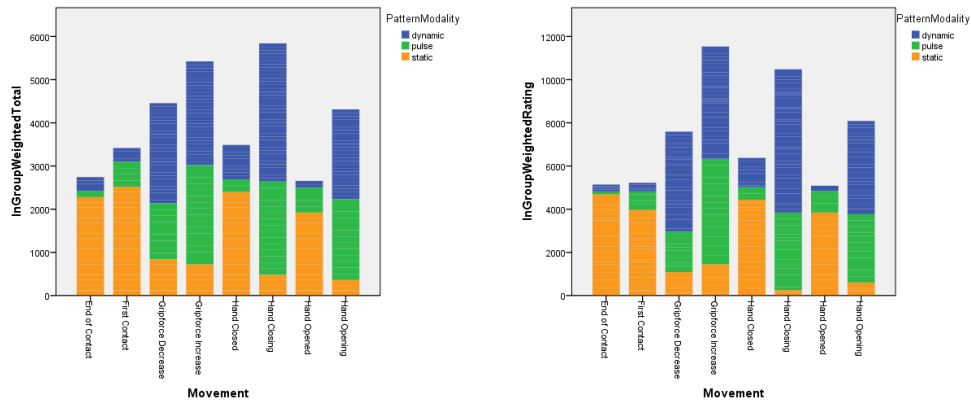
The number of subjects within each group was uneven, as there were seven people in the naive group and eight participants in the instructed group. This was taken into consideration by calculating the InGroup variable for both the weighted number of votes and the consequential weighted rating, in order to be able to compare both graphs.

In Figure 6.16 and Figure 6.17 two types of histograms can be seen, illustrating the relationship between movement and pattern modality. Each pattern modality has a unique color: blue for dynamic patterns, green for pulsed patterns and orange for static patterns. As can be seen at first glance, static patterns were predominantly mapped to the four states Hand Opened, Hand Closed, First Contact and End of Contact, whereas pulsed patterns and dynamic patterns exhibit majority in the dynamic movements Hand Opening, Hand Closing, Grip Force Increase and Grip Force Decrease.

To describe those instances more comprehensively, the histogram in Figure 6.16a shows the distribution of different pattern types among the eight movements. Moreover, it illustrates the number of patterns that were mapped to a certain movement. Since pattern modality was not equally distributed, a weighted total to reflect accurate allocation was calculated (weightedTotal). Also, In this graph, rating is not accounted for, it only shows the number of times a certain movement was mapped to one of the three types of pattern modality.

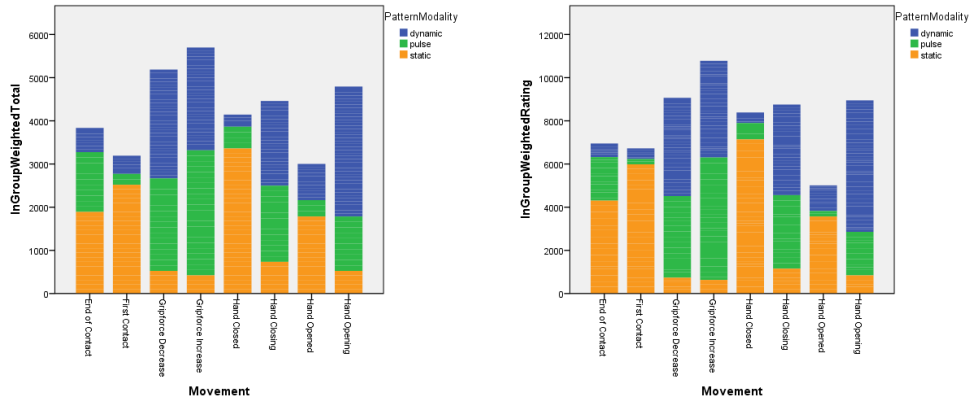
It can be seen that the dynamic movements have more patterns mapped to them than the static movements. The movement with the least amount of mapped patterns to in the graphs of both the naive and instructed group is Hand Opened. The movement getting chosen most for patterns is Hand Closing in the naive group and Grip Force Increase in the instructed Group. The most static patterns were attributed to the static movement Hand Closed in the naive group and First Contact in the instructed Group, whereas most dynamic patterns were mapped to the dynamic movement Hand Closing in the naive group and Hand Opening in the instructed Group. The highest number in pulsed pattern attribution can be found in the dynamic movement of grip force Increase in both groups.

In addition to Figure 6.16a and Figure 6.17a, Figure 6.16b and Figure 6.17b show a histogram of the pattern modality distribution according to the eight movements using the weighted rating. This relativizes the histogram displaying the weighted total of votes as it accounts for the ratings that were given to each vote. In rating it can be seen how sure persons were with their vote and how well the displayed vibratory pattern would correspond to the chosen image of the movement. The rating “Not Really” was not considered within the weighted rating condition, because of the assigned rating of 0 in the analysis (see Table 2). It is, ineluctably, included in the histogram of quantity (Figure 6.16a and Figure 6.17a).



(a) Naive Group: Histogram of Pattern Modality Distribution according to weighted Quantity (b) Naive Group: Histogram of Pattern Modality Distribution according to weighted Rating

Figure 6.16: Naive Group: Histograms



(a) Instructed Group: Histogram of Pattern Modality Distribution according to weighted Quantity (b) Instructed Group: Histogram of Pattern Modality Distribution according to weighted Rating

Figure 6.17: Instructed Group: Histograms

For a better understanding, the static movement End of Contact taken from the instructed group is exemplary for the difference in both type of plots. While in Figure 6.17a the pattern distribution shows a rather big fraction of pulsed patterns and dynamic patterns associated with that movement. In Figure 6.17b however, which accounts for weighted rating, a reduction of those fractions can be seen. Thus pulsed patterns and dynamic patterns may have been a choice for this movement, but in the end a lot of those votes received a poor rating. An accurate comparison of percentages between the weighted total of votes and the according weighted rating can be found in Table 3 to Table 10⁸.

Movement = Hand Opening, Group = instructed

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	43	62,8%	10	26,3%	5	10,9%
InGroupWeightedRating	43	68,1%	10	22,5%	5	9,4%

a. Movement = Hand Opening, Group = instructed

Movement = Hand Opening, Group = naive

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	26	48,2%	13	43,4%	3	8,3%
InGroupWeightedRating	26	53,4%	13	39,2%	3	7,4%

a. Movement = Hand Opening, Group = naive

Table 3: Naive and Instructed Group: Percental Correspondence - Hand Opening

⁸“Summe als Zeilen%” = sum of percentage across rows and “Anzahl” = number of votes

Movement = Hand Closing, Group = instructed

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	28	44,0%	14	39,6%	7	16,5%
InGroupWeightedRating	28	48,0%	14	38,8%	7	13,2%

a. Movement = Hand Closing, Group = instructed

Movement = Hand Closing, Group = naive

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	40	54,8%	15	37,0%	4	8,2%
InGroupWeightedRating	40	63,4%	15	34,4%	4	2,3%

a. Movement = Hand Closing, Group = naive

Table 4: Naive and Instructed Group: Percental Correspondence - Hand Closing

Movement = Gripforce Increase, Group = instructed

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	34	41,8%	23	50,9%	4	7,4%
InGroupWeightedRating	34	41,6%	23	52,6%	4	5,8%

a. Movement = Gripforce Increase, Group = instructed

Movement = Gripforce Increase, Group = naive

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	30	44,2%	16	42,5%	6	13,3%
InGroupWeightedRating	30	45,1%	16	42,4%	6	12,5%

a. Movement = Gripforce Increase, Group = naive

Table 5: Naive and Instructed Group: Percental Correspondence - Grip Force Increase

Movement = Gripforce Decrease, Group = instructed

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	36	48,6%	17	41,3%	5	10,1%
InGroupWeightedRating	36	50,2%	17	41,7%	5	8,1%

a. Movement = Gripforce Decrease, Group = instructed

Movement = Gripforce Decrease, Group = naive

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	29	52,1%	9	29,1%	7	18,9%
InGroupWeightedRating	29	61,1%	9	24,7%	7	14,2%

a. Movement = Gripforce Decrease, Group = naive

Table 6: Naive and Instructed Group: Percental Correspondence - Grip Force Decrease

Movement = Hand Opened, Group = instructed

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	12	28,0%	3	12,6%	17	59,4%
InGroupWeightedRating	12	23,7%	3	5,0%	17	71,2%

a. Movement = Hand Opened, Group = instructed

Movement = Hand Opened, Group = naive

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	2	6,0%	4	21,7%	16	72,3%
InGroupWeightedRating	2	4,7%	4	19,8%	16	75,5%

a. Movement = Hand Opened, Group = naive

Table 7: Naive and Instructed Group: Percental Correspondence - Hand Opened

Movement = Hand Closed, Group = instructed

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	4	6,8%	4	12,2%	32	81,1%
InGroupWeightedRating	4	5,8%	4	9,0%	32	85,1%

a. Movement = Hand Closed, Group = instructed

Movement = Hand Closed, Group = naive

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	10	22,9%	2	8,3%	20	68,8%
InGroupWeightedRating	10	21,3%	2	9,0%	20	69,6%

a. Movement = Hand Closed, Group = naive

Table 8: Naive and Instructed Group: Percental Correspondence - Hand Closed

Movement = First Contact, Group = instructed

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	6	13,2%	2	7,9%	24	78,9%
InGroupWeightedRating	6	7,3%	2	3,7%	24	89,0%

a. Movement = First Contact, Group = instructed

Movement = First Contact, Group = naive

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	4	9,4%	4	16,9%	21	73,8%
InGroupWeightedRating	4	7,7%	4	16,5%	21	75,8%

a. Movement = First Contact, Group = naive

Table 9: Naive and Instructed Group: Percental Correspondence - First Contact

Movement = End of Contact, Group = instructed

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	8	14,6%	11	36,1%	18	49,3%
InGroupWeightedRating	8	9,1%	11	29,0%	18	61,9%

a. Movement = End of Contact, Group = instructed

Movement = End of Contact, Group = naive

	PatternModality					
	dynamic		pulse		static	
	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%
InGroupWeightedTotal	4	11,7%	1	5,2%	19	83,1%
InGroupWeightedRating	4	6,2%	1	2,8%	19	91,0%

a. Movement = End of Contact, Group = naive

Table 10: Naive and Instructed Group: Percental Correspondence - End of Contact

All percentages can be directly compared in between the weighted total and the weighted rating condition, as well as in between naive and instructed groups. For the tables, only the InGroupWeightedRating variable shall be of interest, as it properly reflects the clear preference for a certain movement to pattern allocation. In comparing the rating between the naive and the instructed group, the resulting preferred type of pattern is always the same, apart for one exception in Grip Force Increase, where the choice differed between a dynamic and a pulsed pattern.

In detail, for the dynamic movement Hand Opening, both groups favoured the dynamic pattern, while the naive group showed slightly more variability in their choices. For the dynamic movement Hand Closing it happened the other way round, the instructed group showed more variability in their preferences with the pulsed pattern closely ranked to the dynamic one. Nevertheless, the choice for a dynamic pattern is still the same in both groups. The only disparity can be seen for the dynamic movement Grip Force Increase. The instructed group chose a pulsed pattern closely before a dynamic one, while the naive group chose a dynamic one, but it was a likewise tight choice. For the counter movement Grip Force Decrease, the instructed group again, wavered between a dynamic or a pulsed pattern and eventually the choice for a dynamic pattern prevailed. The naive group chose very clearly a dynamic pattern, even though this group showed slightly more variability.

For all static states there was a distinct and unified outcome. For Hand Opened almost the same percentage was assigned to a static pattern, variability was also almost the same for both groups. For the counter movement Hand Closed, again both groups preferred a static pattern, but the naive group showed slightly more variability. For the state of First Contact with an object, the favoured pattern was also clearly static. The same holds true for End of Contact with an object, a static pattern was rated with 91% by the naive group, while the instructed group showed a less determined percentage and more variability between patterns.

In summary it can be deduced that pulsed patterns seem to work well for instructed participants, as for the dynamic movements Hand Closing, Grip Force Increase and Grip

Force Decrease it was a tough choice between a dynamic pattern or a pulsed one, for the naive as well as the instructed group. But instructed participants tended to chose pulsed patterns more. Furthermore, slightly more variability was expressed within the naive group, but the results are still similar to each other and congruent except for one movement.

6.5.2 Both Groups

Because of the fact that there is no significant difference in the results and deviation in between groups, the subsequent analysis of pattern takes into consideration votes and ratings from both groups combined. The approach is the same as seen in the previous chapter in the separate analysis of both groups.

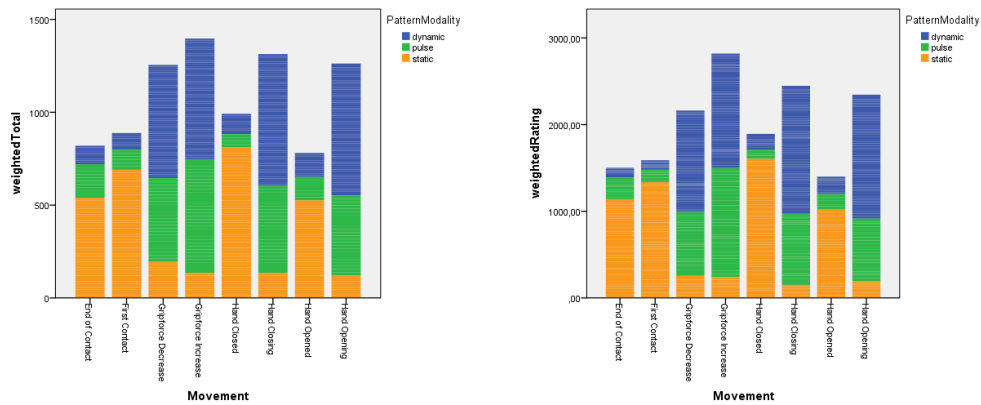
Analogously, the histograms in Figure 6.18 show the pattern distribution of all three pattern types among the eight movements. Figure 6.18a displays the votes cast for a certain pattern while Figure 6.18b shows the respective rating. Since both groups are conjointly analyzed, no InGroup variable is needed. However, pattern modality distribution is still not equal, so weightedTotal and weightedRating still needed to be used.

As in the previous chapter, dynamic movements have more patterns mapped to them then static movements. The movement with the least amount of mapped patterns to in these graphs is Hand Opened. The movement getting chosen most for patterns is Grip Force Increase. The most number of static patterns were attributed to the static movement Hand Closed, whereas most dynamic patterns were mapped to the dynamic movement Hand Closing. The highest number in pulsed pattern attribution can be found in the dynamic movement of Grip Force Increase.

Figure 6.18b displays a histogram of the pattern modality distribution according to the eight movements taking into account the weighted rating of the cast votes. The rating “Not Really” was not considered within the rating condition because of the assigned rating of 0 in the analysis (see Table 2). It is, however, included in the histogram of quantity (Figure 6.18a).

Table 11 to Table 18 provide an accurate percental comparison of both histograms between the given votes and the assigned ratings arranged after movements ⁹.

⁹“Summe als Zeilen%” = sum of percentage across rows and “Anzahl” = number of votes



(a) Histogram of Pattern Modality Distribution According to weighted Quantity (b) Histogram of Pattern Modality Distribution According to weighted Rating

Figure 6.18: Histograms

Movement = Hand Opening

	PatternModality					
	dynamic		pulse		static	
	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl
weightedTotal	56,3%	71	34,2%	24	9,5%	8
weightedRating	61,0%	71	30,7%	24	8,3%	8

Table 11: Percental Correspondence - Hand Opening

Movement = Hand Closing

	PatternModality					
	dynamic		pulse		static	
	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl
weightedTotal	54,1%	71	35,6%	26	10,3%	9
weightedRating	60,0%	71	33,8%	26	6,1%	9

Table 12: Percental Correspondence - Hand Closing

Movement = Gripforce Increase

	PatternModality					
	dynamic		pulse		static	
	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl
weightedTotal	46,5%	65	43,8%	34	9,7%	9
weightedRating	46,8%	65	44,7%	34	8,5%	9

Table 13: Percental Correspondence - Grip Force Increase

Movement = Gripforce Decrease

	PatternModality					
	dynamic		pulse		static	
	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl
weightedTotal	48,6%	61	35,9%	25	15,5%	13
weightedRating	54,1%	61	34,1%	25	11,8%	13

Table 14: Percental Correspondence - Grip Force Decrease

Movement = Hand Opened

	PatternModality					
	dynamic		pulse		static	
	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl
weightedTotal	16,6%	13	16,1%	7	67,2%	35
weightedRating	14,3%	13	12,9%	7	72,9%	35

Table 15: Percental Correspondence - Hand Opened

Movement = Hand Closed

	PatternModality					
	dynamic		pulse		static	
	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl
weightedTotal	11,1%	11	7,3%	4	81,7%	54
weightedRating	9,5%	11	5,7%	4	84,8%	54

Table 16: Percental Correspondence - Hand Closed

Movement = First Contact

	PatternModality					
	dynamic		pulse		static	
	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl
weightedTotal	10,1%	9	12,2%	6	77,7%	46
weightedRating	6,9%	9	9,1%	6	84,0%	46

Table 17: Percental Correspondence - First Contact

Movement = End of Contact

	PatternModality					
	dynamic		pulse		static	
	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl	Summe als Zeilen%	Anzahl
weightedTotal	12,2%	10	22,0%	10	65,9%	36
weightedRating	7,3%	10	16,8%	10	75,9%	36

Table 18: Percental Correspondence - End of Contact

In the next section an in depth analysis of movements and patterns follows. The barplots show the different pattern numbers a movement was matched to. If there is

a pattern missing, it means that this certain pattern was not once chosen to represent that movement. Each block symbolizes one vote and the size of it is equivalent to the weighted rating (gewRating). The color coding scheme of the previous figures is maintained throughout the barplot analysis. Hence blue stands for a dynamic pattern, green for a pulsed pattern and orange for a static pattern. The movement legend to the right of the plot is either colored in blue, to designate a dynamic movement, or in orange for a static movement.

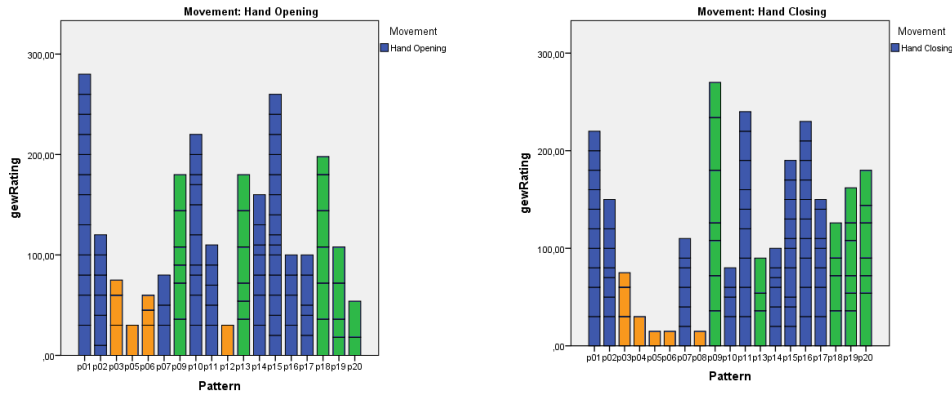


Figure 6.19: Patterns for dynamic Movements: Hand Opening/Closing

In Figure 6.19 the pattern selection for the dynamic movements Hand Opening and Hand Closing can be seen.

Movement: Hand Opening

All nine available dynamic patterns have been considered for the likewise dynamic movement of opening the hand, as well as all five pulsed movements and four out of six static ones. The pattern preferences for that movement are the dynamic patterns p01, p15 and p10, followed by the pulsed patterns p18, p09 and p13. Dynamic pattern p01 scores highest out of all assigned patterns in rating, while pattern p15 scores in total numbers of votes. This means while pattern p01 received a higher rating from the persons who chose it, pattern p15 was chosen more often but rating was less high. The total number of votes this movement received is 98.

Movement: Hand Closing

As in Hand Opening, also in the movement Hand Closing, all available nine dynamic patterns have been chosen, as well as all five pulsed patterns and five out of six static patterns. The preferred patterns for mapping the closure of the hand are by a vote of 10 times each, dynamic pattern p01, p15 and p16. Highest ranking for rating achieved pulsed pattern p09. With 9 votes and highest rating among the dynamic patterns, pattern p11 poses a compromise in votes and rating. 102 votes in total were cast for this movement.

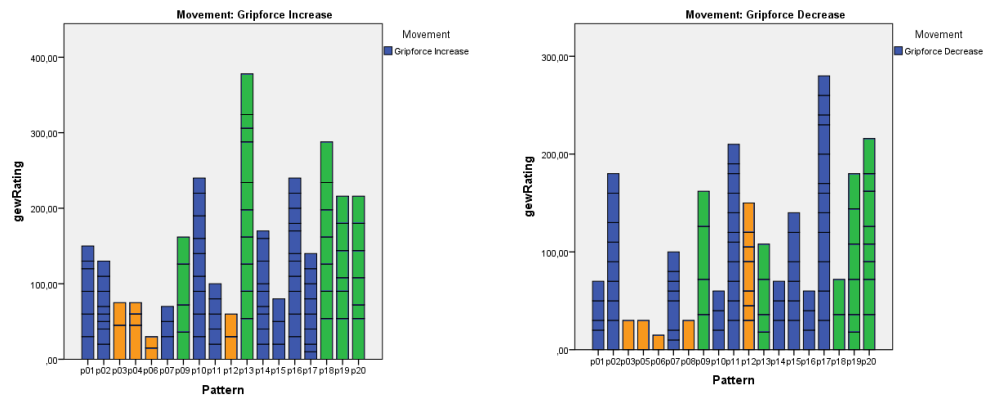


Figure 6.20: Patterns for dynamic Movements: Grip Force Increase/Decrease

In Figure 6.20 the pattern selection for the dynamic movements Grip Force Increase and Grip Force Decrease are illustrated.

Movement: Grip Force Increase

Grip Force Increase is a movement that received a lot of votes for the mapped patterns. All nine dynamic patterns are present as well as the five pulsed ones. Only four out of six static patterns have been voted for. Patterns most chosen by vote are the dynamic patterns p16, p10 and p14, and the pulsed pattern p13, which also places first in terms of ranking by a margin of 1/3rd. All pulsed patterns attained a higher ranking than the dynamic ones according to the votes they received. Even though the dynamic patterns p16 and p11 received 11 votes and 9 votes respectively, they only ranked third compared to the pulsed patterns p13 seizing 10 votes and pattern p18 with only 7 votes. The total amount of votes cast for this movement over all patterns is 104.

Movement: Grip Force Decrease

In contrast to the counter movement Grip Force Increase, the graph illustrating the pattern propensity for the dynamic movement Grip Force Decrease displays no clear preference for pulsed patterns. Again, all nine dynamic, as well as the five pulsed patterns and five out of six static patterns are employed. Ranked highest in terms of votes are dynamic patterns p11 with 11 votes and pattern p17 getting 12 votes, whereas for pulsed patterns the most votes were given to pattern p20 with 8 votes. Even though pattern p20 only received 8 votes, it ranks higher in rating than dynamic pattern p11 which actually achieved 11 votes, but ratings were not favourable and thus p11 places third. The most votes and highest rating gained the dynamic pattern p17, with 12 votes. This movement received 12 votes less than its opposite direction, making it 92 votes.

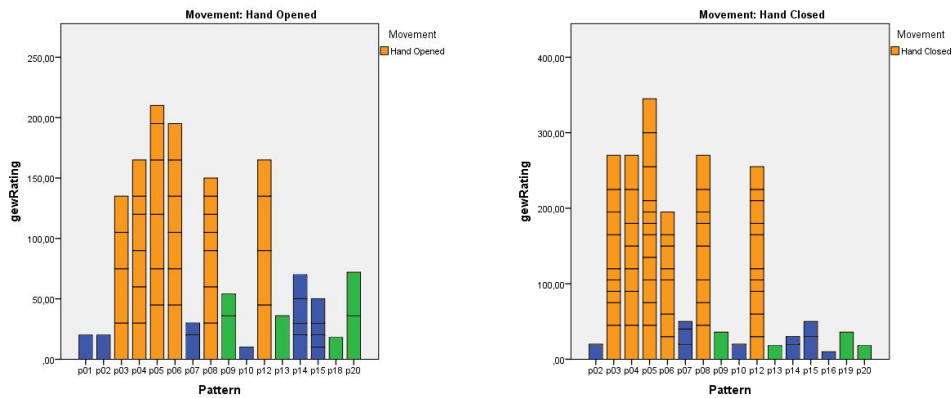


Figure 6.21: Patterns for static States: Hand Opened/Closed

In Figure 6.21 the pattern selection for the static movements Hand Opened and Hand Closed are shown.

Movement: Hand Opened

The graph shows a distribution of all six static patterns, six out of nine dynamic ones and four out of five pulsed patterns. Pattern p08 gained 7 votes and pattern p04, p05 and p06 each got 6 votes. Though pattern p08 only ranked fifth regarding rating. However, pattern p05 placed highest in terms of rating overall, even though pattern p04, p05 and p06 all had the same number of votes. The total votes number up to 52 for this movement over all patterns.

Movement: Hand Closed

Pattern distribution in the plot for Hand Closed is dominated by all six static patterns in both votes and rating. As it has already occurred in Hand Opened, two third of the dynamic patterns (6/9) have been voted for, with a maximum vote of 3 times per pattern and four out of five pulsed patterns are shown with a maximum vote of 1. Ranking highest for cast votes are static patterns p05 acquiring 11 votes and p12 with 10 votes. Pattern p05 not only acquired the most votes, but also the highest rating, awarding it the most preferred pattern for the the closed state of the hand. The total number of votes for this movement and over all patterns is 66.

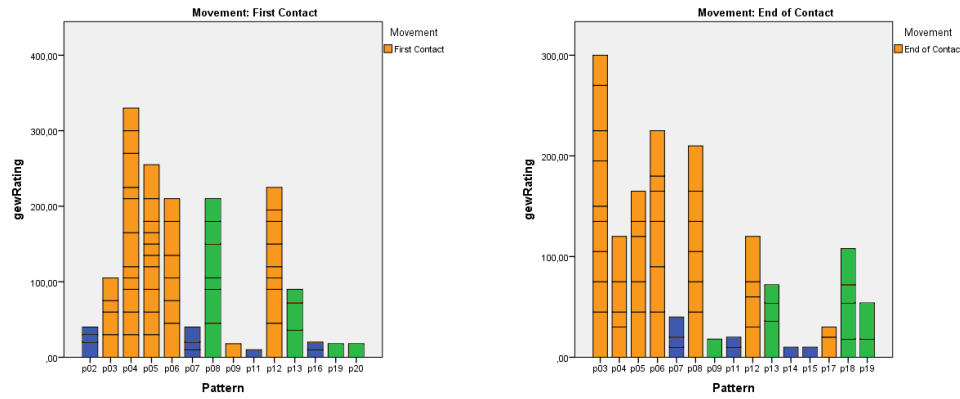


Figure 6.22: Patterns for static States: First Contact/ End of Contact

Figure 6.22 shows the pattern selection for the static movements First Contact and End of Contact.

Movement: First Contact

The pattern distribution in the graph for First Contact shows, that this movement received a lot of votes accumulated among the static patterns. One pulsed pattern however, pattern p08, received 6 votes, the same amount as static pattern p06 and more than likewise static pattern p03. All six static patterns are shown, as well as four out of nine dynamic ones and four out of five pulsed patterns. 60 votes were cast for this movement in total. The most votes were cast for static pattern p04 with 11 votes, followed by pattern p05 with 10 votes and pattern p12 with 8 votes, all of which are static. Pattern p04 received not only the most votes, it also placed first in terms of rating. Second best rated pattern is pattern p05.

Movement: End of Contact

In the graph for the static state End of Contact, all six static patterns are to be seen, only four out of nine dynamic patterns and four out of five pulsed patterns with maximum 4 votes. Cast votes on the static patterns also accompanied high rating. Static pattern p03 received 9 votes which were mostly of high rating, placing this pattern first overall. Second in terms of rating placed the equally static pattern p06, having received 6 votes with all except one of high rating. Also receiving 6 votes but placing third in regard to ranking is static pattern p08. The total amount of votes cast for this pattern is 53.

6.5.3 Mapping Results

After analyzing the statistics of each of the eight movements to one or more of the 20 generated patterns, a distinct pattern can consequently be assigned to one movement. The detailed examination results in the following mapping: For the dynamic movement Hand Opening the most votes were cast for the dynamic pattern p15, the best rating, however, received dynamic pattern p01. The counter movement Hand Closing displayed ambiguous preferences, the pulsed pattern p09 ranked highest, closely followed by the dynamic pattern p11 which exceeded pattern p09 in votes, but not rating. For the

dynamic movement Grip Force Increase, the dynamic pattern p16 received the highest count of votes, but is far behind the pulsed patterns in ranking. The pulsed pattern p13 was ultimately preferred for indicating increase in grip force. As for Grip Force Decrease, the dynamic pattern p17 received the most votes and is ranked first in preferences. Although the pulsed pattern p20 followed closely in terms of rating.

To indicate the static state of Hand Opened, the static pattern p05 was ranked highest, just barely before static pattern p06. A clear mapping is identifiable for the static state of Hand Closed, as the static pattern p05 received the most votes as well as the highest rating. For both of those states, basically every static pattern was in the run, as all of them received high votes and ratings, and the choice for the overall best fitting pattern was a narrow one. Quite differently so for the static states of First Contact and End of Contact, where pattern assignment was clear-cut. For First Contact, static pattern p04 ranked highest and for End of Contact, static pattern p03 was evaluated best.

A summarized overview of the above results can be seen in Table 19.

Movement	Pattern by Ranking	Pattern Modality
Hand Opening	p01	dynamic
Hand Closing	p09, (p11)	pulsed, (dynamic)
Grip Force Increase	p13	pulsed
Grip Force Decrease	p17	dynamic
Hand Opened	p05, (p06)	static, (static)
Hand Closed	p05	static
First Contact	p04	static
End of Contact	p03	static

Table 19: Overview: Mapping of Pattern to Movement

6.6 Summary and Discussion

This study sought after two goals: The first was to generate a pool of vibratory patterns that comply with the vibel matrix about sensory discrimination obtained in the psychometric assessment in Chapter 6. The second was to evaluate those patterns in order to come up with a particular mapping of one pattern to one of eight prosthetic movements, which could be furthermore implemented as haptic feedback into a prosthesis. For an actual prosthetic implementation, feedback would only be provided when the prosthesis is actively moving or just finished moving, but not when it perseveres in one position. This is based upon the fact, that especially change is regarded as important for the brain, whereas constant conditions do not need to be communicated. The movements, which were to be coded with vibratory patterns, were inspired by recent surveys among prostheses users and split up in two categories, one category standing for dynamic movements and one for static events.

To adhere to the resolution of the vibel matrix, the amplitude range was split into 15 steps, that encompassed 21% of the highest resolution within the matrix, and the frequency range into seven steps, that represent 24% in the matrix. Combinations always follow the structure of one out of 15 steps of amplitude associated with one of the seven frequency steps for at least one and maximum nine combinations per pattern. Although, to also incorporate the phenomena, that with increasing frequency the amplitude appears

to rise as well, a higher frequency of 30% corresponding to 75Hz just outside the resolution sector had also been considered as well.

The generation of patterns was inspired by the psychological effect of intuitiveness and the field of psychoacoustics. Though intuitiveness has proven to be of beneficial utilization, extensive research in psychoacoustics lead to the conclusion that only a limited number of phenomenons could be incorporated into the pattern design. By referring to intuitive concepts such as automation, familiarity and previously acquired knowledge to the vibratory feedback patterns, users should improve quickly in controlling their prosthesis. The predominantly subtle vibration patterns should relate to that previously acquired knowledge, for example to the vibratory expression of the sound released by a beeper of a parking car, to create an intuitive feeling of movement. Intuition would take place as a response to those vibration patterns.

While psychoacoustics was primarily used to generate the vibration patterns with additional attending to intuitiveness, intuitiveness was moreover used in an experimental setting to evaluate those vibration patterns. It was investigated by splitting the participants into two groups: one naive group that received just the basic explanations and the interface introduction, and an instructed group that received explanations and presentations about different pattern types. The performance in both groups was quantified to analyze statistical differences and commonalities. The vibratory feedback patterns were intuitive enough, so that movement and pattern mapping was almost identical in both groups and all subjects reported the same pattern modality preference for the same movement.

In the end, it was possible to create a catalog of vibration patterns in which one pattern maps for a distinct movement. Although it can be seen in the results that pattern p05 maps for both states Hand Opened and Hand Closed. It still would not be constructive to assume that there might be no clear distinction in the perception of those movements, as they represent their complete opposite. It is likely the nature of the pattern that was so versatile as to be mapped to both movements. In case of such overlapping, it can be decided to take the next best pattern chosen for one of those two movements. In this case, it would be wise to choose the movement Hand Opened, as the second best static pattern p06 is ranked just closely behind pattern p05, and let pattern p05 code for the static state Hand Closed.

This catalog of patterns does not need to be adapted to every new person as it represents an average preference over able bodied persons. The possible patterns do not differ exorbitantly in their structure, so the basic arrangement would remain the same. Additionally, the brain is capable of learning and assigning meaning to those patterns. Even if a person would display difficulties while interacting with the feedback patterns, they would eventually learn what kind of pattern maps to which movement. The brain will adapt and recognize each pattern.

However, there could be differences in sensitivity between healthy and impaired participants. Thus it could be a next step to evaluate this set of vibration patterns in experiments conducted with amputees or to implement these patterns into a prosthesis and test real time performance.

7 Discussion and Future Prospects

Intuitive and natural behaviour of grasping and holding relies on sensory input from either the surrounding or the perceiving body itself. It is no surprise that this concept was also taken into consideration in the development and design of artificial limbs. As such, control would be improved if the prosthesis and its user would be able to take advantage of both exteroceptive and interoceptive information.

Research in sensory feedback for upper limb prostheses focuses mainly on sensory substitution as feedback method and myoelectric, battery-powered prostheses as medium. In this thesis, vibrational feedback was employed, which is especially interesting for commercial application, because vibration motors became popular through various consumer electronics, such as smartphones and game controllers. As a result, not only acceptance for vibration motors has increased, they are also available off the shelf, which makes them low in price and high in energy efficiency. Though for conventional vibration motors, amplitude and frequency are not independently adjustable.

Since sensory substitution does not employ the actual sensed modality, it is important not to forget that sensory perception is an integration of many different impressions. The movements that were coded in this thesis do not account for surface texture, for example. Texture is just another form of vibration, composed of different frequencies and amplitudes. Different vibrations could produce the sensation of different textures, such as the smooth skin of a banana or the fur of an animal.

Apart from texture, also temperature has not been coded, or object consistency. It is a difference if someone tries to grab a cold iron bar or a hot jelly pudding. Humans use all the environmental information to subsume them into a holistic sensory experience. Combining different feedback modalities would provide prosthetic users with an authentic feeling of their surroundings. However, it is barely possible to implement one feedback system. By mounting more than one feedback system, conflicts among them could arise, restraining or disabling each other. Besides, it is also a challenge to apply the feedback motor to the amputee's stump, since not all patients possess a sufficiently large stump. Also, there are electrodes used for moving the prostheses, with whose myoelectrical signal the feedback system should not interfere.

There furthermore exists another source of feedback that is not as apparent as the reviewed feedback methods. Patients also use the inherent, actually undesired, feedback elicited by, for example, the motor of the prosthesis. By activating the artificial limb, signs of wear appear over time and the prosthesis tends to increase its working volume. This kind of auditory feedback is used by amputees to aid their movements. It happened that patients, handing in their prosthesis for repair, complained that this prosthesis is not their own and could not operate it as skillfully as they used to do so before. An effect that occurred because of the now missing unwanted feedback, which was repaired.

It can be assumed, that the known types of feedback mostly act on the conscious level. While generating the vibration patterns for the second experiment, vibrations were made to linger at the threshold of perception, in order to let them be perceived on an unconscious level¹⁰. As the first experiment presented in this thesis shows, participants could very well perceive and act on sensations they claimed were too subtle to

¹⁰Although there are also some less delicate patterns which are easily perceivable.

feel. Automatically running processes require less cognitive effort and increase intuitive behaviour. Another aspect of intuitiveness that was not ventured into during this thesis, is the physiology of the stump. Different sensory areas can be found on the amputee's stump, which moreover belong to a map of the body. It is possible to, for example, map the finger locations on the stump. Applying feedback specifically at those areas would provoke a more physiologically integrated perception of the feedback, because the stimulation would feel as if it would come directly from the fingers.

In this way, the location of the actuator, or the actuators, is an important factor to consider. For the psychometric and pattern experiments of this thesis, the motor was placed on the forearm near the elbow, because tissue there is a good combination of softness and hardness. But of course there exist other possible placements, which would be worth looking into. Also taking into consideration the different levels of amputation and the density of mechanoreceptors in the skin, which decreases towards the back and differs between glabrous and non-glabrous skin.

Not only the location of the actuator is of importance, also the timing of the created feedback stimuli. Delay time of the sensory input leads to distorted perception and an incongruent image of the surrounding. To still grant integration, delay should be in the order of milliseconds. Also, the sensory input should be discrete and not continuous. A continuous stimulus not only is annoying during everyday life, but is also prone to adaptation. Novel stimuli are of importance for the brain, because it masks out constant excitation of receptors.

Regarding the brain, it would also be of interest to have a look at its plasticity, how it reorganizes due to the loss of a limb and the consecutive re-introduction of feedback. This could be examined in both short term and long term studies to gain insight into the long term effects of sensory feedback.

Before, mapping of the stump was mentioned. This relates to plasticity, as many patients still feel their missing hand as an extension of the stump and experience phantom pain. Over time, phantom pain decreases in magnitude, which could be due to cortical plasticity. Phantom pain has been extensively researched, but it would be interesting to see, how patients that receive sensory feedback develop in regard to embodiment: do they see the artificial limb as part of their own or do they maybe perceive the stump as their phantom hand, because sensory input is felt at this site?

As of today, there are no commercially prostheses available that employ intended sensory feedback. In this regard, prosthetic limb users still have to largely rely on visual monitoring. "Ironically, after decades of research in upper limb prosthetics, robotics, haptics and applied neuroscience, it is the very simple architecture of the body-powered prosthesis dating back to 1912, that remains the only device coming close to providing physiologically correct and acceptable sensory feedback to the user" (Antfolk 2013:7).

Zusammenfassung

Intuitive Vibrotaktile Feedback Muster für Prothesen der oberen Extremität

Ein bedeutender Aspekt für Amputierte der oberen Extremität ist die Kontrolle der Prothese. Die Interaktion mit der Umwelt ist für die Betroffenen eine Herausforderung, da durch den Verlust der sensorischen Wahrnehmung wichtige Anhaltspunkte fehlen. Durch sensorisches Feedback wird die Steuerung jedoch zunehmend intuitiver.

Darauf eingehend, ist das Ziel dieser Arbeit, Vibrationsmuster zu generieren und zu evaluieren, um diese letztendlich für haptisches Feedback in Prothesen bereit zu stellen. Zurzeit besteht die einzige Möglichkeit, Informationen über das Prothesenverhalten in Erfahrung zu bringen, indem die Nutzer ihre Bewegungen visuell überwachen, welches eine hohe kognitive Belastung darstellt.

In einem ersten Experiment wurden psychophysische Messmethoden angewandt um vibrotaktilen Feedback als eine geeignete haptische Stimulationsmethode zu identifizieren und ein Skalierungssystem zu schaffen, an dem sich die tatsächliche Mustergenerierung in einem zweiten Experiment orientiert. Sowohl das erste als auch das darauf folgende Experiment wurden mit dem gleichen Stimulationsmotor, welcher auf den unteren Arm gesunder Versuchspersonen angelegt war, durchgeführt. Um den Mechanorezeptoren der menschlichen Physiologie zu entsprechen, wurden Vibrationen bis zu einem maximalen Bereich von 60Hz eingesetzt.

Des weiteren war die Mustergenerierung inspiriert durch andere Disziplinen, wie Psychologie und Akustik, die eine Basis für Intuitivität und Vertrautheit schaffen sollten. Dadurch sollte die Musteridentifizierung und -zuordnung besonders leicht fallen.

Drei verschiedene Arten von Mustern wurden erzeugt: statische, dynamische und pulsierende. Alle unterschieden sich in ihren Amplituden- und Frequenzkombinationen, so wie in den Pausenzeiten zwischen den einzelnen Teilstimulationen. Die generierten Vibrationsmuster wurden in einem anschließenden Experiment hinsichtlich ihrer Intuitivität und Zuordnung zu einer der folgenden prothetischen Bewegungen evaluiert: Griffkraft ansteigend oder abfallend, geschlossener oder geöffneter Zustand der Hand, Schließen und Öffnen der Hand, sowie Erstkontakt mit einem Objekt und Kontaktende. Diese kann man unterteilen in vier dynamische Bewegungen und vier statische Zustände. Versuchsteilnehmern wurde ein Muster appliziert und sie mussten wählen zwischen zwei als Fotos vorgegebenen Bewegungen, die sie mit diesem Muster kodieren würden. Anschließend wurde diese Wahl von den Teilnehmern bewertet, bevor sie das nächste Muster erhielten.

Die Auswertung der Daten zeigt eine eindeutige Zuordnung von statischen Mustern zu statischen Zuständen und dynamischen und pulsierenden Mustern zu dynamischen Bewegungen. Außerdem lässt sich je ein Muster pro Bewegung identifizieren, welches das am meisten gewählte, als auch das am besten bewertete ist.

In dieser Hinsicht lässt sich ein Vibrationsmusterkatalog erstellen, der als Leitfaden für den Einsatz von vibrotaktilen Feedback in Prothesen der oberen Extremität herangezogen werden kann. Diese Applikation würde Prothesenträgern eine genauere und intuitivere Kontrolle ermöglichen und die daraus resultierende kognitive Anforderung senken.

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Curriculum Vitae

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Education

2005 – 2013	Psychology at University of Vienna
2007 – 2010	East Asia Studies (Japan) Bachelor course at University of Vienna
2010 – 2012	Middle European interdisciplinary master programme in Cognitive Science (MEi:CogSci) at University of Vienna and Medical University of Vienna
1998 – 2005	„Ernst-Fridrich-Gymnasium“ Secondary School in Berlin (Germany)

Internship

October 2007 - February 2007	Research Internship at the department for Forensic Diagnostics concerning Psychosis at the general hospital AKH Vienna (supervisor at University of Vienna and Medical University of Vienna: Univ.Prof.Dr.Mag. Ulrike Willinger)
February 2011 - July 2011	Research Project at Austrian Institute of Technology (AIT) to evaluate the Emotiv EPOC EEG headset and implement an EP based BCI (supervisor at AIT: Dr. Tilmann Kluge)
February 2011 - July 2011	Research Project at Otto Bock Vienna about sensory feedback and body awareness in upper limb amputees (supervisor at Technical University of Vienna: Ao.Univ.Prof. Dipl.-Ing. Dr.rer.nat. Dr.techn. Dr.scient.med. Frank Rattay)
October 2011 - February 2012	Research Project at the clinical neurophysiology department of the medical hospital of Ljubljana in electrodiagnostic medicine about conduction velocity in the ulnar nerve (supervisor at the hospital: Dr. Janez Zidar).

Work

September 1st 2012 - February 28th 2013	Otto Bock Healthcare Products GmbH - Full Time Employee at the Strategic Technology Management (STM) for Master-thesis project „Intuitive vibrotactile Feedback Patterns for Upper Limb Prostheses“
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