Towards a Tactile Language for Movement Instructions

Diploma Thesis at the
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Contents

List of Figures

List of Tables

Declaration

I hereby declare that I have created this work completely on my own and used no other sources or tools than the ones listed, and that I have marked any citations accordingly.

Hiermit versichere ich, dass ich die Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

(Anke Hilgers)

Abstract

In everyday life and sport activities an adequate body posture is required to avoid consequential injuries. Feedback on the actual body posture is required to improve the posture.
In this thesis we present full-body tactile movement instructions as a way to assist in achieving maintaining the correct posture. As different domains of everyday life and sport have specific movements in common we identified basic movement instructions. To provide a basis for tactile pattern design, we defined a structure of a tactile language. On the basis of this structure several full-body tactile patterns were designed.
In order to validate our design and to narrow down the number of patterns, we performed a user test in which we examined the intuitiveness of the designed tactile patterns. This allows to assign specific movement instructions to specific tactile patterns. In Addition it was examined if these association can be learned and subsequently be remembered in a cognitive demanding task.
The test revealed that users are able to interpret and apply our tactile movement instruction patterns both in relaxed condition and under cognitive load.
Finally we tested a selection of our designed tactile movement instructions in one of the previously identified sport applications (horse riding). Again the participants were able to distinguish the tactile movement instructions with high accuracy.
In relaxed condition the overall identification accuracy of the tactile movement instructions is 95% while it is only slightly decreased in the cognitive demanding condition.
Our results of this thesis advise that tactile feedback is an appropriate instrument to give information about the actual body posture even during physical activities. While doing so rabbit patterns are favored as they do not only indicate the body location which is affected by the movement but also the direction of the movement. Because of the underlying structure the basis for a "universal" tactile language for full-body movement instructions is founded within this thesis.

Überblick

Um Schäden und Verletzungen zu verhindern, ist es sowohl im alltäglichen Leben als auch beim Sport notwendig, eine gesunde Körperhaltung einzunehmen. Um dies zu gewährleisten benˆtigt man Informationen über die aktuelle Körperhaltung und wie diese bei Bedarf zu korrigiert werden kann. In dieser Arbeit beschäftigen wir uns damit, diese Information mittels taktiler Bewegungsanweisungen zu übermitteln.

Im ersten Teil dieser Arbeit haben wir die taktilen Patterns entwickelt. Hierbei wurde ausgenutzt, dass verschiedenen Bereichen im alltäglichen Leben sowie im Sport ähnliche Bewegungen gemein sind. Daher konnten wir grundlegende und allgemeingültige Bewegungsanweisungen identifizieren. Darüber hinaus haben wir eine Struktur einer taktilen Sprache definiert auf Grundlage derer wir eine Vielzahl von taktilen Patterns für den ganzen Körper entwickeln konnten.

Im zweiten Teil haben wir die entwickelten Patterns in verschiedenen Benutzerstudien untersucht. Um die Patterns auf ihre Eignung zu untersuchen, haben wir in einem Benutzertest die taktilen Patterns hinsichtlich ihrer Intuitivität getestet. Dadurch war es uns möglich, Bewegungsanweisungen bestimmten taktilen Patterns zuzuordnen. Zusätzlich haben wir diese Assoziationen hinsichtlich ihrer Lernbarkeit untersucht und getestet, ob diese auch unter kognitiver Belastung umgesetzt werden können. Die Untersuchung zeigte, dass Anwender die taktilen Bewegungsanweisungen sowohl ohne als auch mit kognitiver Belastung interpretieren und anwenden können.

Zum Schluss haben wir eine Auswahl der taktilen Bewegungsanweisungen in einer der zuvor identifizierten Anwendungen unter realen Bedingungen getestet. Erneut waren die Teilnehmer in der Lage, die taktilen Bewegungsanweisungen mit hoher Genauigkeit zu identifizieren. Ohne kognitive Belastung ist die gesamte Identifikationsgenauigkeit der taktilen Bewegungsanweisungen 95%, mit kognitiver Belastung vermindert sich diese nur wenig.

Die Ergebnisse dieser Arbeit zeigen, dass taktiles Feedback ein geeignetes Instrument ist, um Informationen über die aktuelle Körperhaltung zu vermitteln. Dies ist auch unter kognitiver Belastung möglich.

Als Bewegungsanweisungen sind Patterns zu bevorzugen, die neben der Körperstelle, die durch die Bewegung beeinflusst wird, auch die Richtung der Bewegung vorgeben. Wie diese Patterns und weitere Typen von Patterns kombiniert werden können, um neue Patterns zu entwickeln, ist durch die Struktur der taktilen Sprache festgelegt. Anhand dieser zu Grunde liegenden Struktur ist eine Basis für eine universelle Sprache für Bewegungsanweisungen für den ganzen Körper in dieser Arbeit geschaffen worden.

Acknowledgements

This thesis would have never been possible without the help and support of many people, all of whom I owe my gratitude.

Many thanks to Daniel Spelmezan, my thesis advisor, for always taking the time for meetings, suggestions, and constructive criticism.

I want to thank Prof. Dr. Jan Borchers for introducing me to the field of HCI, for teaching a different perspective in many issues, which encouraged me to take this path.

I also want to thank Prof. Wolfgang Prinz for having agreed to be my second examiner.

Special thanks to all of you, who participated in the several user tests. With your help I gained valuable feedback for improving the tactile movement instructions. Additionally I want to thank Mareike Jacobs for the real good collaboration during the user tests.

Thanks to Tim Arping, IKV Aachen, who allowed me to use his experimental setup to determine the frequency of the employed vibration motors.

Finally I want to thank my family for always supporting me.

Thank you!

Conventions

Throughout this thesis the following conventions will be used:

The plural “we” will be used throughout this thesis instead of the singular “I”, even when referring to work that was primarily done by the author.

The whole thesis is written in American English.

Chapter 1

Introduction

1.1 Thesis Aims

Today people are faced with an information overload and processing this information poses a challenge. Especially people with physical impairments consequently often are not able to cope with this amount of information. Therefore it has to be targeted to find new ways for transmitting information to reduce the load on classical information channels. One way to do this is through touch. The tactile channel has often been used to substitute audio and visual information as is shown in chapter 3—"Related work".

Tactile channel to substitute audition and vision

A lot of applications exist which make use of tactile feedback. Many include applications in the field of sensory substitution, providing navigational information, enhancement of mobile phone applications, and tactile user interfaces.
Less investigations are done in the field of daily and sport activities. In everyday life and sport activities we have to maintain a good body posture to avoid consequential injuries. There are already investigations in monitoring the user's body posture and giving feedback to the user but this feedback is mostly limited to visual and auditory channel. In cognitive demanding environments these channels may already be heavily overloaded so that there will be a loss of information.

Monitoring body posture

Tactile movement instructions

Therefore the goal of this diploma thesis is to find new domains for full-body tactile feedback and to investigate how to design tactile feedback patterns for these domains in order to provide full-body tactile movement instructions. As a further step we like to find a "universal" language for full-body tactile feedback. Designing "universal" feedback will provide the possibility to apply tactile patterns to a broad field of applications, where movement corrections are required.
This poses several questions:

- Which domains can benefit from full-body tactile feedback?
- Which body parts can be used for tactile feedback?
- How to encode information via vibration? Which patterns are most natural or most easy to learn?
- How does cognitive workload and physiologically demanding tasks influence the recognition of the patterns?
- Does a "universal" full-body tactile language exist and how does it has to be constructed?

1.2 Thesis Structure

To answer these questions,

Chapter 2—"Basics" gives an introduction of the tactile sense. It is compared to the two mostly used senses that are vision and audition. Subsequently the sensation and perception of touch is described in detail.
Finally the hardware employed in this thesis is introduced.

Chapter 3—"Related work" gives an overview of work done in the field of tactile feedback in different domains. Through this common used tactile parameters. Moreover body locations are identified.

Chapter 4—"Designing the Tactile Feedback Patterns" describes the tactile design. First a collection of daily and sport domains is presented from which basic movements are deviated. On the basis of a tactile language tactile movement instructions are designed. Furthermore an overview of the garment design is given.

Chapter 5—"Evaluation of the Designed Patterns" contains the different user tests which have been conducted to validate and further improve our design. It is examined what people intuitively associate with the designed movement instructions and how they recognize the patterns with and without cognitive load or physiologically demanding tasks.

Chapter 6—"Summary and Future Work", finally, gives an overview of this work, summarizes the tactile design and evaluation, and states the principal achievements of this thesis. As this thesis marks the initial step in designing a tactile language for movement instructions, the chapter outlines further improvements of the tactile design which should be validated in future work.

Chapter 2

Basics

"I do not feel obliged to believe that the same God who has endowed us with sense, reason, and intellect has intended us to forgo their use."

— Galileo Galilei

2.1 Common Senses for Perceiving Feedback

In this thesis we want to find new domains for tactile feedback. To clarify why we use tactile feedback instead of using another sense for giving feedback about body posture corrections, we will describe in the following all three common senses. Therefore we first describe the characteristics of visual, auditory, and tactile feedback and in which way tactile feedback can complement the other two senses in situations where these are already or will be overloaded. Subsequently we further describe the sensation and perception of touch. Finally the hardware is introduced that is used in this thesis.

2.1.1 Visual Feedback

Vision is a spatial sense

Vision and audition are the two senses mostly used for information transmission. The sense of vision is characterized by its spatial nature, which in special situations can be a drawback. Since vision is spatial, people realize only things, which are in their field of vision and will miss things, which are aside of it. In these situations the use of an additional sense, like audition or touch, would be appropriate to shift the user's locus of attention to an occurrence beside the field of vision. One example of this problem is a car driver who focuses either to the street or to, for example, the navigation system. The use of alternative senses can support the driver to keep his attention to the street, while simultaneously getting information about his route. Of course there are also advantages of vision over other senses like audition. Through visual displays it is possible to transmit information to people in cases that the surrounding environment is too noisy.

Visual Icons

Visual icons are graphical symbols that visually represent information. A popular example for the use of icons are computer displays [Blattner et al., 1989].

Icons need small amount of space and speed up information transmission

One great advantage of visual icons is that they can convey complex information in a small amount of screen space, much smaller as for textual description. With the graphical representation the information can be presented concisely if the meaning of the icon is familiar to the user. Through visual icons the visual information transmission is accelerated.

Visual icons are not culturally independent. The same icon can differ in meaning in different cultures. As Raskin [2000] further states, icons are most effective when their number is limited.

An overly dense visual display leads to cognitive overload, which will lead to a decrease in the decision-making performance of the user. Especially in devices with small or with no visual displays (like mobile phones) it is helpful to use alternative senses to transmit information to the users. In everyday live situations occur where the user is not able to use the visual sense, for example, when the mobile phone is in the trouser pockets. In these cases alternative feedback like auditory and tactile feedback is appropriate and is described in the following.

2.1.2 Auditory Feedback

Auditory feedback is used to transmit information like warning signals. With this kind of feedback it is possible to transmit information to the user, while he is not paying attention to it.
This grabbing of attention can also be disadvantageous because the user's locus of attention is suddenly directed to something different, which may lead to the loss of his locus of attention [Raskin, 2000].

Audition is a temporal sense

Another drawback of auditory feedback is its temporal nature. An information given once will not occur another time unless a repetition is intended beforehand. So if the user misses the message because he is not in the proximity of the sender or the environment is to loud, he will not get the message another time.
In general auditory feedback is not private. Everybody in the proximity of the user can also hear the information and can feel disturbed. To overcome the privacy problem the user could wear headphones, but is then isolated from the environment. The use of tactile feedback can be a better alternative if the application is, for example, a mobile application.

Earcons

The aural counterpart to visual icons are earcons. Like icons they are used to speed up information transmission and in case that the user's attention has to be grabbed.

Earcons need short amount of time

Earcons are brief, structured sound patterns. With earcons it is possible to convey information in a short amount of time compared to synthetic speech. Earcons can be composed by manipulating parameters such as frequency, pitch, rhythm and loudness, which can be modified to get new, distinguishable earcons [Blattner et al., 1989, Brewster et al., 1993, 1996]. Auditory icons are another form of icons for auditory feedback. They make use of natural sounds to represent specific items or events [Gaver, 1989], while earcons use structured sound patterns, which constitute a counterpart to speech.

Auditory icons use natural sounds.

2.1.3 Tactile Feedback

A rarely used sense for giving feedback is touch, although it combines important aspects of vision and audition and therefore shows a good potential as a communication medium [Brewster and Brown, 2004b]. Touch is a spatial as well as temporal sense, so the disadvantages of vision and audition, being either spatial or temporal, do not apply.

Touch is a spatial as well as temporal sense

Touch is a discreet, obtrusive, private and attention grabbing sense that leaves hands, ears and eyes free [Brown, 2007]. Because the whole body is able to recognize touch the display area available for transmitting information is quite large.

Like the previously described senses the sense of touch has also disadvantages. Compared to audition the resolution is limited. This means that people are not able to feel the same small differentiations as they would be able to hear. Therefore tactile feedback cannot completely replace the sense of audition, but in combination with its spatial nature it is a good medium to complement it.

Touch can complement other senses

Another drawback of the tactile feedback is that a tactile message can also be masked by other touch sensations that are not part of the message. Especially in environments, where environmental vibrations exist or other sensations like pain occur, it has to be explored if tactile messages are masked.

To get known to the sense of touch we will describe the characteristics of touch in the following as well as aspects and parameters that are necessary for the design of tactile feedback.

Tactile Sensation and Perception

The skin as a communication medium

Touch is always transmitted through the skin. The skin is a big, sensitive area and is one of the largest organs of our body. It insulates inner body from outside influences and thereby protects the body against bacteria, chemical matters and dirt. The main function that is of special interest for us is its ability to perceive information of different impulses that affect the body like temperature, pain, touch, or force.

How do we perceive touch?

The first question that arises is how we perceive touch. To answer this question we will describe how the skin is composed and which components are responsible for the perception of touch.

Touch is a somatic sense, a body sense. Haptic is an often related keyword to the sense of touch, which is derived from the greek word ”haptesthai”, which means ”contact” or ”touch”.

Kinesthetic and cutaneous perception.

The somatosensory system is composed of cutaneous sensing and kinesthetic sensing. Tactile sensing refers to an awareness of stimulation to the outer surface of the body, while the kinesthetic sensing refers to an awareness of limb position and movements as well as muscle tension [Tan, 2000].

Touch is bidirectional

The haptic sense is a bidirectional sense [Tan, 2000], because it consists of the sensing environment, which is responsible for the perception of temperature, vibration, and texture, and the manipulation environment, which is responsible for the human ability to push, pull, pinch, hit, and rotate things. Many activities require the use of both sensing and manipulation as drafted in figure 2.1. People who read Braille have to move with their fingers over the embossed paper while their fingertips perceive the texture.

Passive and active information reception

The somatosensory system differentiates between passive and active information reception. The active information reception describes the bidirectional nature whereas the

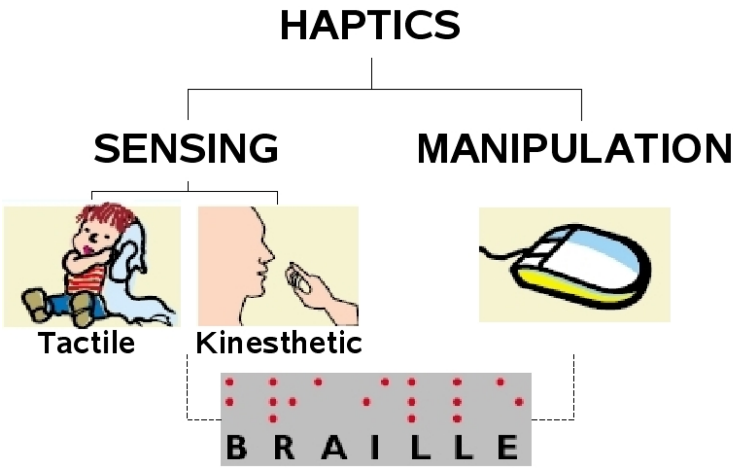


Figure 2.1: Definition of Haptics [Tan, 2000]

passive information reception only affects the receptors in the skin. People are not able to control passive information reception. The tactile feedback we will use in this thesis belongs to the passive information reception.

The skin is composed of layers. We will only focus our attention to two of these. The outer part of the skin, the epidermis, and the inner part of the skin, the dermis, which contains nerve endings of the cutaneous receptors. Cutaneous receptors include, for example, cutaneous mechanoreceptors, nociceptors (pain) and thermoreceptors (temperature).

Mechanoreceptors are responsible for tactile perception

Mechanoreceptors are responsible for tactile perception and pertinent to detect vibrotactile stimuli. Four types of mechanoreceptors are shown in Figure 2.2. The mechanoreceptors differ from each other for example through their different rates of adaptation to stimuli. Based on this adaptation the mechanoreceptors can be divided into two groups. There are slowly adapting (SA) receptors and rapidly adapting (RA) mechanoreceptors. The SA receptors respond continuously during the stimulus, while the RA receptors respond only at start and end of the stimulus. The RA receptors are responsible for the fact that we are not aware of wearing our clothes.
Other characteristics of mechanoreceptors are the size of their receptive field as well as the form of impulse to which

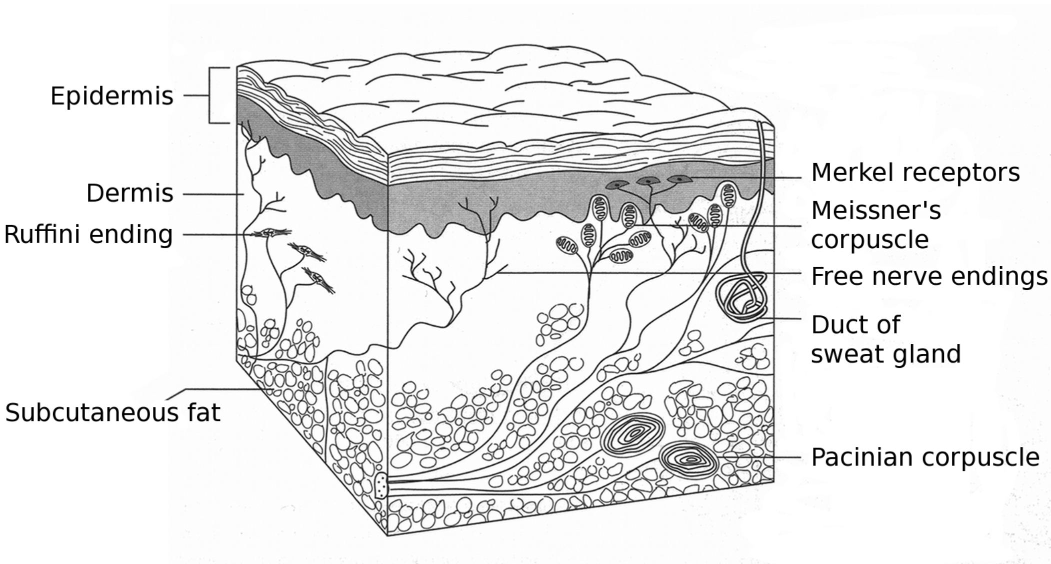


Figure 2.2: Cross section of glabrous skin to show the location of the mechanoreceptors [Goldstein, 2002]

Mechanoreceptor	**Merkel's disc**	**Meissner corpuscles**	**Ruffini corpuscles**	**Pacinian corpuscles**
Perception	light touch	pressure	stretch	vibration
Frequency	0.3-3 Hz	3-40 Hz	15-400 Hz	10 > 500 Hz
Receptive field	small	small	big	big
Adaptation	slow	rapid	slow	rapid

Table 2.1: Characteristics of the different mechanoreceptors [Goldstein, 2002]

the mechanoreceptor is most sensitive.

The four mechanoreceptors with their different characteristics are described in table 2.1 in the order of their location in the skin starting with those closest to the epidermis. Because of their position in the skin, the outmost receptors already react to light touch, whereas the more internal receptors are responsive to higher pressure.

Pacinian corpuscles

Most relevant for our work are the Pacinian corpuscles that respond to vibration stimuli. They have a big receptive area and are able to detect a broad range of vibrotactile stimulations. Their maximum sensitivity occurs between 200-300Hz [Verrillo and Gescheider, 1992].

Distribution of tactile sensors

For the appropriate design of tactile feedback, it is very important to know about the distribution of tactile sensors. With the knowledge of the distribution we are able to decide which body locations can be considered to be used for giving tactile feedback.

Figure 2.3 shows the proportion of the somatosensory cortex that is devoted to each part of the skin. The figure shows that some areas of the skin like the fingers, lips, and tongue, are more densely supplied with nerve fibers than others. These are represented by larger areas of the somatosensory cortex. The larger the areas for specific body parts in the somatosensory cortex are, the more detail these body parts are able to differentiate when a tactile stimulus is applied.

Another significant factor about the distribution of mechanorecptors is that there are more receptors in glabrous skin than in hairy skin, making it more sensitive to stimulation.

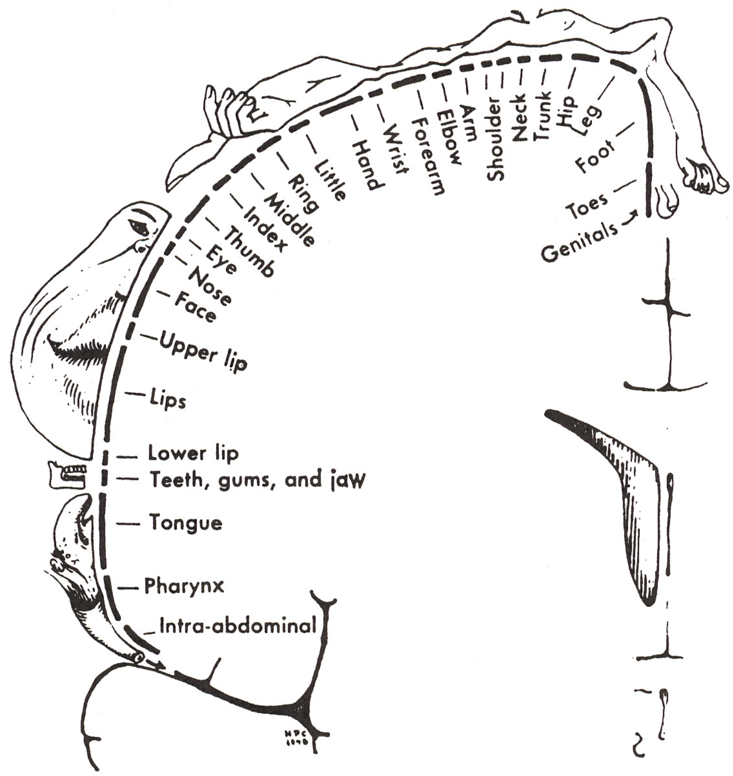


Figure 2.3: Cutaneous representation in the brain [Schiffman, 2001]

The spatial resolution is dependent on the density of the receptors and the area of somatosensory cortex which are devoted to the specific body region. The more receptors are in a region of the skin and the larger area is in the somatosensory cortex the higher is the resolution.

Tactile resolution

To provide information about the distance, which is necessary to distinguish to separate points on the skin, a measure, called the two-point threshold, is introduced.

Two-point threshold

The two-point threshold is the smallest distance between two points on the skin at which these can barely be perceived as two discrete points. Different body areas have different two-point thresholds as is shown in figure 2.4. To measure two-point thresholds on different body areas two pencils are hold next to each other and touch simultaneously the skin. If only one point of contact is perceived, the spacing between the two pencils is enlarged until two discrete points are perceived. As can be seen in figure 2.4

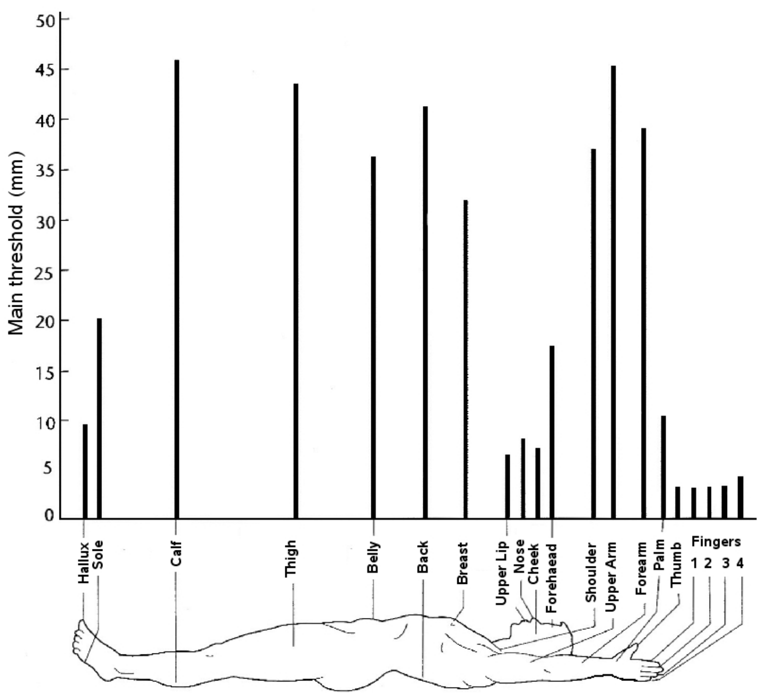


Figure 2.4: Two-point threshold [Goldstein, 2002]

people react very sensitive to touch at their fingers, in their face, and on their feet. In these areas the two-point threshold is very low. Accordingly the receptor density in this regions is very high. The area of the somatosensory cortex devoted to this areas can be seen in figure 2.3. We also know that, for example, fingers are quite sensitive to two-point discrimination (c.f. figure 2.4).

Braille

Because of these circumstances it is understandable why trained people are able to read Braille letters. A typical braille letter is only 6 mm high, 4 mm wide, and consists of 6 dots, which are arranged in a rectangle of 2 columns of 3 dots. The letters differ from each other through small raised or even dots. Blind people achieve a reading rate of 200 words per minute, which is not as fast as the visual reading rate, which averages 250-300 words per minute, but is quiet impressive (Schiffman [2001] and Goldstein [2002]).

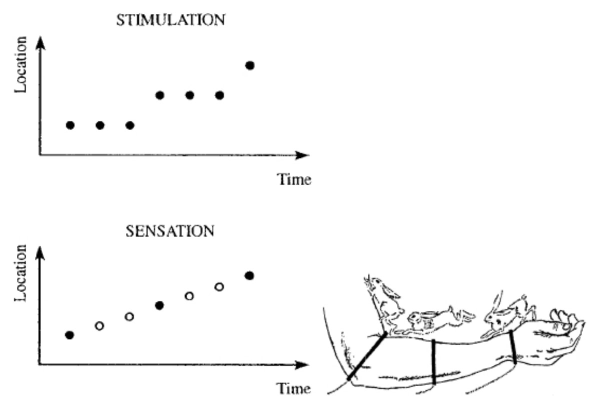
People are less sensitive to touch on their legs, torso, and arms. The highest two-point threshold is measured for calves and for upper arms. In these areas two points have to be more than 45mm apart to be perceived as two discrete points. Although the density of receptors in the fingers is very high, we will not use this body location in this thesis in order to leave the hands free for other applications.

Sensory Saltation

Having described the characteristics of mechanoreceptors and the tactile resolution, we now want to introduce the sensory saltation phenomenon. Sensory saltation is a tactile illusion that was discovered by the US psychologist Frank A. Geldard in 1972. The illusion occurs if three light vibration stimuli are given in quick succession at region of the body, for example, the forearm. The first and second are given on the same spot whereas the third is given a few centimeters away. The effect is that the second tap is felt very distinctly to have occurred at a point somewhere between the first and the third tap [Geldard and Sherrick, 1972]. A draft of this phenomenon can be seen in figure 2.5 (a). In the figure the actual stimulation and the perceived stimulation are pictured. Three vibration pulses are given at the first location, then three vibration pulses at the second location followed by one pulse at the third location. Instead of perceiving this seven pulses at the actual location, the pulses seem to be evenly distributed.

Cutaneous Rabbit

The sensory saltation phenomenon is also called the cutaneous rabbit because of the perception of the three taps, which feel like a rabbit hopping along the arm, see figure 2.5 (b).



(a) (b)

Figure 2.5: Sensory Saltation [Tan and Pentland, 1997]

After we have presented how people perceive touch, we now will introduce tactile icons, so called Tactons, which are the counterparts to visual icons, earcons and auditory icons. Afterwards we will present the hardware that is used during this thesis.

Tactons

Before we direct our attention to Tactons haptic icons have to be explained. Haptic icons are "brief information rich computer generated signals" [Fisher et al., 2004], which are displayed to a user by force feedback or tactile feedback . Force feedback stimulates the kinesthetic sense while tactile feedback stimulates the cutaneous sensing. Force feedback devices are important in teleoperation and virtual reality systems by improving an operator's task performance and by enhancing a user's sense of telepresence [Tan, 2000]. A popular example for a force feedback device is the PHANTOM by Sensable Technologies[1] .

Haptic icons: force or tactile feedback

In the following we concentrate on haptic icons that are displayed through tactile feedback. These are called tactile icons or shorter Tactons. Brown et al. [2005] give the following definition for Tactons: "Tactons are structured, ab-

Tactile icons = Tactons

[1] http://www.sensable.com/products-haptic-devices.htm

stract, tactile messages, which can be used to communicate information non-visually".

Tactons are tactile counterparts to icons and earcons

Tactons are designed in the same way as graphical icons and earcons to speed up the information transfer, but their meaning has to be learned. Previous work on earcons has shown that learning and memorizing the meaning is possible and be done quickly [Brewster, 1998].

As Tactons act both spatially and temporally, they are able to complement visual icons, which are spatially, and earcons, which are temporally.

Parameters of Tactons

Like earcons, Tactons encode information by manipulating the parameters of cutaneous perception [Brewster and Brown, 2004a]. These parameters are frequency, amplitude, waveform, rhythm, and body location.

Frequency

Frequency is referred to the vibration rate, the speed at which the vibration motor rotates. The range of perceivable frequencies is between 20 and 1000 Hz, but the maximum sensivity is around 250 Hz [Gunther et al., 2002].

Amplitude

Amplitude, on the other hand, deals with the intensity of the vibration. Amplitude and frequency are addicted to each other. A change in amplitude leads to a change in the perception of frequency. As the amplitude of vibration is increased the vibratory pitch (perceived frequency) is decreased [Rothenberg et al., 1977]. Therefore either frequency or amplitude should be manipulated to create tactile patterns.

Waveform

The term *waveform* points to the shape of the vibration wave. Users can differentiate only a few different waveforms, which are sine waves and square waves [Gunther et al., 2002]. The vibration motor that is used in this thesis, produces sine waves.

Duration

Through pulses of different *durations* it is possible to encode information. The duration of a tactile pattern should be chosen long enough to be detected, but should not slow down information transfer. Geldard [1960] defined the usable range of durations from 100 milliseconds to 2 seconds.

Rhythm

Rhythm is like in sound a very powerful application. By putting together pulses and gaps of different durations a rhythm is generated, which forms a temporal pattern.

Body Location

The *body location* points to the location where the vibrotactile stimulus occurs on the user' body. The different body locations have different levels of sensivity and acuity (c.f. figures 2.3 and 2.4). Although the skin provides a big area for placing vibration motors not all body locations are appropriate for perceiving vibrotactile feedback, especially the hands should be kept free for other applications.

3 primary tactile parameters

Not all transducer allow to manipulate all types of the previously described parameters for the tactile design but Geldard [1957] states that the three primary and independent parameters of vibratory cutaneous stimulation are amplitude, duration, and body location. Before we will have a look at the related work in the context of tactile feedback, it is first explained what a tactile display is and which kind of hardware is used in this thesis to give tactile feedback.

The hardware used in this thesis is described in the following section.

2.2 Hardware

After we have discussed the advantages and disadvantages of the three common senses, vision, audition, and touch with a closer look at the perception of touch and its possibility to use it to communicate information, we will now have a closer look at the hardware used to present tactile feedback to the user.
Since the designed Tactons are tested in the real environment of an application, for example like horse riding, a wearable tactile device is needed. In previous work about the monitoring of body postures for snowboarding, a device, the SensAct box [Guggenmos, 2007, Schanowski, 2008], based on an Arduino microcontroller board[2] , is developed.

SensAct box

In the following we will describe the SensAct box as well as the vibrotactile actuators employed together with this box

[2]http://www.arduino.cc

to give tactile feedback.

2.2.1 SensAct Box

The SensAct box (figure 2.6) consists of an open-source ArduinoBT board, which can be programed in a C-like language.

Analog and digital communication

The output ports of Arduino boards can be addressed via analog or digital commands. Analog signals just offer the parameters 0 ("Off") or 1 ("On") for controlling devices connected to the output ports of the board. Digital communication permits a technique called pulse width modulation (PWM) that basically encodes analog signal levels digitally by modulating the duty cycle of the signal, thus regulating the amount of power that gets sent to an output port [Barr, 1999]. With analog communication the vibrotactile actuator would vibrate with full power or would be off, while with digital communication it is possible to adjust the intensity with which the motors vibrate.

Pulse Width Modulation (PWM)

A custom motor shield was developed at our group on the top of the Arduino to allow direct attachment of sensors and actuators [Spelmezan et al., 2008]. The used SensAct Box (figure 2.6) consists of six sensor connectors, eight actuator connectors, an ON/OFF button and a status LED, which offers the user information about the state of the hardware, such as booting, running, streaming, or low battery status. In this thesis six vibrotactile actuators are connected to each SensAct box to give tactile feedback.

Connection via Bluetooth

To address the actuators manually we use the two-way Bluetooth Serial Port Profile to connect the SensAct Box either with a computer or with a mobile phone. Thereby instructions can be send to the SensAct Box, for example, which actuator has to start or stop its feedback. The type of vibrotactile actuator we use during our work is described in the next section.

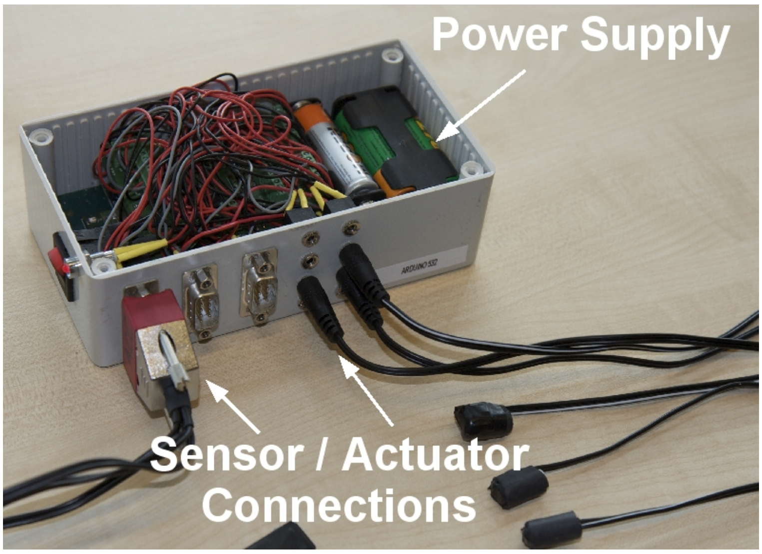


Figure 2.6: SensAct Box

2.2.2 Vibrotactile Actuators

One of the most important vibrotactile actuator is a vibration motor that is a small DC motor with eccentric mass on its shaft. A DC control signal causes the rotation of the vibration motor that in turn generates the vibration pulses.
Two different types of vibrotactile motors exist that are pancake/coin and cylindrical vibration motors. Both types produce vibration by rotating a mass. The significant difference between those two vibration motor types is the axis of rotation. The pancake motor produces vibrations parallel to the surface on which the motor is mounted. While the cylindrical vibration motors produce vibrations orthogonal to the surface.
In the following we decide to use cylindrical vibration motors because they produce the best perceivable vibrations, which corresponds to the investigation of Piateski and Jones [2005]. In figure 2.7 both motor types are pictured.

2 types of vibrotactile actuator: pancake and cylindrical motor

Since the cylindrical actuator is originally designed for the use in a Nokia 3210 mobile phone, it is packed in a case, which allows free rotation of the mass. In the figure 2.7 the

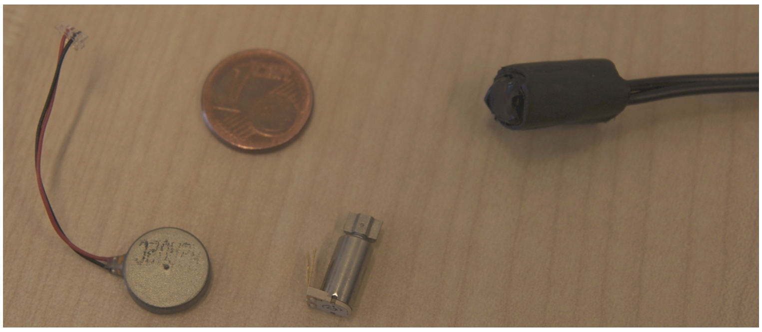


Figure 2.7: Pancake (left) and cylindrical motor (center and right) in comparison to a one cent coin

cylindrical motor is once pictured without the surrounding case (in the middle) and once with a case. The attached cable at the cylindrical vibration motor facilitates connecting the motor easily to a SensAct box.

Although the employed cylindrical vibration motor requires high spin-up times to reach desired amplitudes, they are very adequate for our purpose, because these motors are comparably cheap, approximately five euro and easy to get in designated electronic stores. In comparison the tactile actuators used in another application for giving tactile feedback, the Tactaid[3] , allow very quick ring-up and ring-down times, but are, with US$81, very expensive.

Frequency Analysis

In the context of this thesis we use vibration motors developed for the use in mobile phones. It is important to know the frequency the employed vibration motor can achieve as the maximal vibration sensivity occurs around 250 Hz [Gunther et al., 2002]. Unfortunately we could not find data about the achieved frequency of the employed vibrating motor.
Therefore the frequency is determined with the help of a Brüel & Kjaer accelerometer (Type 4393V), which is attached to the motor through superglue, see figure 2.8.

[3] http://www.tactaid.com/

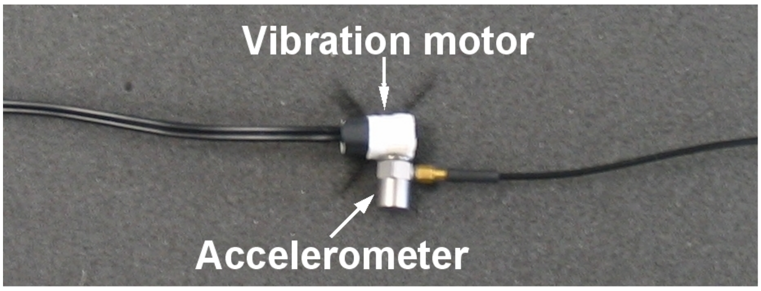


Figure 2.8: Vibration motor with attached accelerometer

To avoid that the measurement is affected by a movement of the vibration motor and the sensor, they are hold in a fixed position during the testing. Due to the low mass of the vibration motor, the frequency can also be affected by the cables and the underlay. Therefore the motor is fixed between two foam layers to assure similar conditions for all tested vibration motors.

It is necessary to mention that the foam also influences the frequency of the vibration motor. Therefore the measured frequencies are lower than those you can measure if the vibration motor is unrestrained. But in this thesis the vibration motors will be attached to the clothes of the users, so the vibration motors are not unrestrained either.

The frequency is determined through a Fast Fourier Transformation (FFT) of the acceleration. The tested motor is activated for 100ms starting with 0% of the power (0 PWM) and increasing it up to 100% of the possible power (255 PWM) of the vibration motor. The power is increased in steps of 5 PWM, which is about 2%. The frequency is measured for each of the given PWM signals, which are controlled by the Haptic Editor [Jonas, 2008].

In the following figure 2.9 the measured frequencies of the three tested vibration motors are shown.
The test reveals that each of the three tested vibration motors has different characteristics. With a given PWM signal of, for example, 255 the frequency varies between 194 Hz for motor 2, 176 Hz for motor 1, and the lowest 169 Hz for motor 3. This yields in an average maximum frequency of

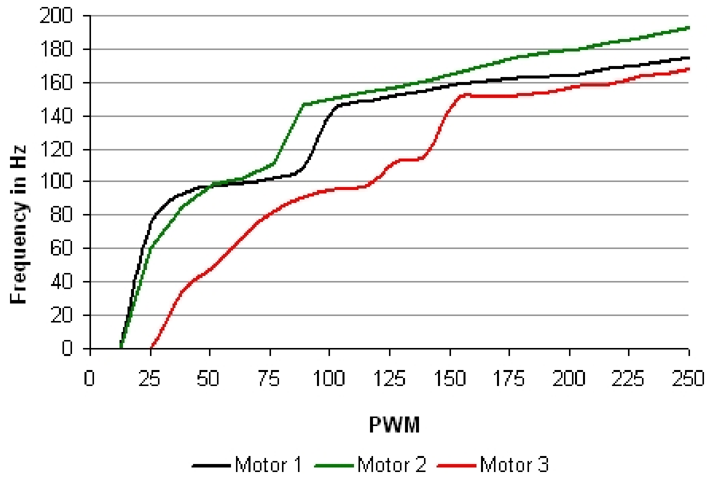


Figure 2.9: Achieved frequency against given PWM signal of the three vibration motors

180 Hz.
All tested motors show a jump in frequency from around 110 Hz to 140 Hz although the PWM signal only increases about 13 PWM, which as shown in figure 2.9.
Significantly is that the correlation between PWM and frequency is not linear, but roughly exponential.

The obtained measurements show differences between the tested vibration motors but by giving them a signal of 255 PWM (or an analog signal of "1") they all achieve a frequency zone, which is adequate for our application, namely up to 200 Hz. If there are different frequencies to be used, the different characteristics of the vibration motors will be of more interest.

The employed vibration motors do not support all parameters of cutaneous perception, but like Geldard [1957] stated, the three primary tactile parameters are body location, duration and amplitude.

Chapter 3

Related work

> *"What is research but a blind date with knowledge?"*
>
> *— Will Harvey*

In the following we present important papers in the field of tactile feedback, which are relevant for the work in this thesis.

Tactile feedback might be beneficial in the following applications: Tactile User Interfaces (TUI), medical applications (minimally invasive surgery), rehabilitation, entertainment, military applications, education and haptic warning signals. In this chapter we introduce some of the systems for the mentioned applications. The research work to be reviewed is divided into six subchapter, but sometimes it is not possible to allocate a work to a specific subchapter as the topic may overlap.

3.1 Tactile Feedback for Sensory Substitution

The work on haptic displays was first motivated by the desire to develop sensory-substitution systems for visually and hearing impaired. Examples include the Optacon

[Linvil and Bliss, 1966], a reading aid for the blind, and TactaidVII[1] , a hearing aid for the deaf [Tan, 2000].
With the Optacon (OPtical-to-TActile-CONverter) blind people achieve immediate access to printed media. Only one forefinger is necessary to "read". The Optacon consists of a camera, which allows the user to scan a paper, and a small display consisting of rows of vibrating peds, which displays the image of the media to the user's forefinger.
Tactaid VII is a tactile aid which presents coded sound information via seven vibrators. The user gains sound information by feeling the rhythm, duration, intensity, and pattern of the vibrations. These coded vibratory patterns are unique, consistent and learnable.

Two further approaches try to find solutions for different problems that occur to visually impaired people. On the one hand it is important to people to improve their mobility, which includes avoidance of obstacles in the immediate path [Cardin et al., 2006]. The second covers the field of spatial orientation and way finding. For visually impaired it is necessary to have a good spatial orientation to establish and maintain an awareness of one's position in space relative to landmarks in the surrounding environment and relative to a particular destination. Through their spatial orientation visually impaired people are able to find their way regardless of the need to avoid or move around obstacles in their path.

Obstacle Detection

Cardin et al. [2006] try to help visually impaired by improving their mobility through obstacle detection, which is displayed to them by vibro-tactile feedback on the torso. Ultrasonic transducers mounted on the torso emit and measure the echo of ultrasonic waves (see figure 3.1). Depending on the measured distance to the closest obstacle the voltage output of the corresponding vibrator changes. Investigations showed that equipped users are able to walk through a corridor in a reasonable time after a short time of training. This system helps visually impaired people to independently explore their environment.

Ross and Blasch [2000] cover the domain of spatial orientation and way finding. In their work they compare three

[1] http://www.tactaid.com/

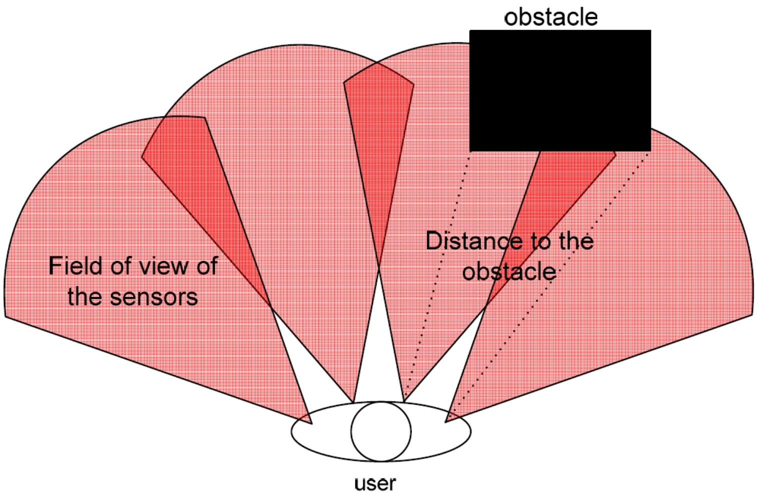


Figure 3.1: Obstacle Detection by ultrasonic Transducers [Cardin et al., 2006]

wearable orientation interfaces: a stereophonic sonic guide, a speech output, and a shoulder-tapping system.

Situation Awareness

The shoulder-tapping system first consisted of a 3x3 tapping interface (small speakers) on the back of the user's torso, which was reduced after the first tests to only three shoulder tappers. If the user is on target, the center tapper will produce a double-tap every two seconds. If the user is off-target by 7.5 degrees right or left, then the left or right tapper respectively will tap in addition to the center tapper. If the user is off-target by 15 degrees or more, only the left or right tapper respectively will tap in response. This shoulder-tapping system assists people with severe visual disabilities in walking a much straighter path across the street as was determined by a user test.

Tactile Memory Game

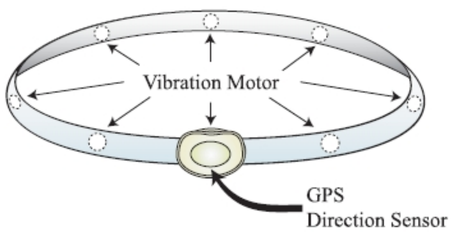
Raisamo et al. [2007] develop a tactile memory game. The user has to remember different vibrations instead of sound or embossed pictures that are common in memory games for blind children. The game is designed to be played with a tactile gamepad. The gamepad has two vibration motors to produce tactile feedback. By manipulating tactile parameters, distinguishable tactile pairs are developed for the memory game. Instead of using the standard parameters of tactile feedback, explained in 2.1.3—"Tactons", they use roughness and rhythm. The three designed pairs of patterns are labeled with: decreasing and increasing, two-rhythm and four-rhythm, gentle and intense.

3.2 Tactile Feedback for Navigation

As we have seen in 3.1—"Tactile Feedback for Sensory Substitution" tactile navigation aids are mainly developed to support visually impaired. In this section we want address other applications for tactile navigation. Especially in applications where other senses, which are essential for navigation, are already overloaded.
Tactile applications for navigation are of special interest to our field of research. With navigations aids the whole body of a user is directed into one direction. These approaches are important, because they give ideas how it will be possible to indicate the user to only direct parts of the body into a direction to correct body posture.

ActiveBelt for navigation

Tsukada and Yasumura [2004] develop the ActiveBelt, which is a belt-type wearable tactile display for directional navigation. A belt is attached around the torso, which consists of a GPS sensor, a direction sensor, and 8 vibration motors. In figure 3.2 a basic concept of this ActiveBelt is pictured.



(a)

Figure 3.2: Sketch of the concept of the ActiveBelt [Tsukada and Yasumura, 2004]

Four applications are thought of where the ActiveBelt will be beneficial that are called FeelNavi, FeelSense, FeelSeek, and FeelWave. FeelNavi is a navigation aid, FeelSense a location-aware information service, FeelSeek helps to remember and find valuable objects with the help of RFID chips, and FeelWave is for entertainment.

FeelNavi

Through FeelNavi the wearer of the ActiveBelt gets directional cues. If a specific motor vibrates the user has to walk toward the direction of the vibration to reach his destination. The distance to the destination is indicated by pulse intervals of vibration. When the user comes closer the vibration intervals become shorter. A user test has shown that users should get vibration impulses only when they are aside their destination.

GentleGuide

Another simple wayfinding system, the GentleGuide, was developed by Bosman et al. [2003]. Pedestrians are guided indoors through a building by vibration pulses activated by two wrist-mounted devices. Four types of directions are indicated by different durations of the vibration pulses. A 700 msec lasting vibration pulse on one wrist indicates the user to go to this direction, a 700msec lasting pulse on both wrists suggests that the destination is reached, and finally a vibration pulse of 1500msec on both wrists indicates a wrong direction. He stated that vibrations are interpreted as beacons to follow, rather than as a correction nudge for one's direction. In contrast to the previously described way finding system [Ross and Blasch, 2000], it was observed that people find their way with the wrist-mounted device, but without deriving a spatial orientation.

In-vehicle navigation

A similar approach is used by van Erp and van Veen [2001] for an in-vehicle navigation system. The vibrotactile stimuli presented under the leg indicate the direction the driver has to go. Vibration triggered under the left leg signifies a left turn whereas vibration under the right leg signifies a right turn.

Tactual Situation Awareness System (TSAS) for pilots

More complex vibrotactile feedback was also used, for example, in systems to assist a pilot. Rupert [2000] tries to find a solution for spatial disorientation (SD) mishaps in aviation by a Tactical Situation Awareness System (TSAS). In the past pilots could maintain pitch and roll by referring to the horizon, but in situations where the horizon is not in sight, while it is for example cloudy, this reference point does not exist any more. For this situations a lot of visual available instruments were developed to help the pilot monitor the orientation of the airplane. Visual instrument scanning is recognized to be a challenging mental task, which still can lead to SD mishaps. To further reduce the number of SD mishaps tactile cues are tested to help the pilot maintain normal orientation and control over an aircraft. Therefore multiple tactors are placed on a torso suit to represent combinations of roll and pitch. The gravity vector direction is displayed to the pilot as the point or center of the area on the torso that would experience pressure in the normal earth condition.

Collision Detection in VR

Another domain where tactile feedback is needed are virtual environments. The visual feedback alone does not overcome the loss of the physical sense of confinement and constraint in virtual worlds. To address this issue, Bloomfield and Badler [2007] and Schätzle et al. [2006] developed vibrotactile collision feedback to the user's arm in virtual environments. It is shown that the use of vibrotactile feedback on the user's arm improves performance in the virtual environment. If the operator's arm collides with an object of the virtual reality (VR), the collision situation will be computed and displayed through a vibrotactile feedback device. This can be, for example, used to for assembly verification in a Virtual Reality system. To get fully immersed in a virtual environment, a full-body haptic feedback is required [Schätzle et al., 2006].

Situation Awareness in VR

Lindeman et al. [2006b] provide directional cues with their TactaBox in order to increase situational awareness in both real and virtual environments. The TactaBox is a control box that can address actuators like the SenseAct box used in this thesis. Through a TactaBelt, in which eight tactors are arrayed around the torso, situational awareness in, for example, a building-clearing task in VR can be increased. The vibrotactile cues denote areas of the space that the wearer is exposed to, but has not yet viewed. As Bloomfield and Badler [2007] they also used the system for collision detection in a virtual environment. Another application Lindeman et al. [2006a] thought of is described in 3.5—"Monitoring Postures in Sport and Daily Activities".

Situation awareness in hazardous environments

Through the "haptic radar" developed by Cassinelli et al. [2006] users were able to avoid unseen objects. This is helpful in hazardous working environments. The "haptic radar" is a headband that consists of infrared proximity sensors and vibration motors. If, for example, a building worker is not aware of a steel beam approaching from behind he will be announced by a vibration stimulus at the corresponding site and can sidestep, see figure 3.3.

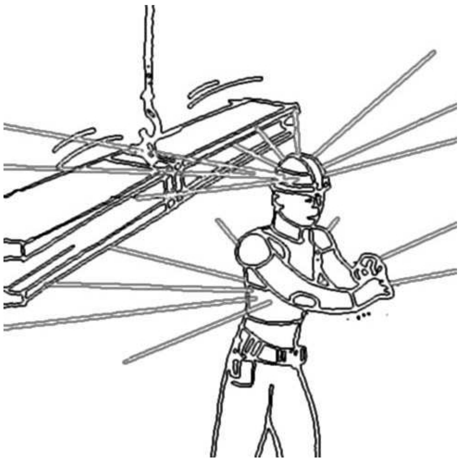


Figure 3.3: Operation Method of the Haptic Radar [Cassinelli et al., 2006]

The papers, introduced so far, use simple vibrational cues to direct the user in real or virtual environments. The last two papers we want to describe use more complex patterns, which make use of the sensory saltation phenomenon to give directional cues.

Sensory saltation for giving directional cues

Tan and Pentland [1997] were one of the first who use a tactile directional display, called the "rabbit" display, with a two-dimensional stimulation array on the back of the user to explore the cutaneous rabbit (see 2.1.3—"Tactile Sensation and Perception"). The tactile stimuli, displayed to the back of the user, can elicit vivid movement sensation like up, down, left, or right. As the directional cues are intuitive and relative to the user's own body coordinate they require no additional coordinate information.
The first version of the tactile display consisted of a three-by-three array, but in the final version a four-by-four array was used to avoid stimulation to the spine area [Tan and Pentland, 2005]. In an implementation of a navigational guidance system, the tactile display has been integrated into a driving simulation software system to provide di-

rectional information to the driver like turn left, turn right, or go straight at the next intersection. In this situation the driver feels a left, right or upward arrow on his back.

A similar tactile display on the torso as a navigation aid was explored by Jones et al. [2006]. With their four-by-four array they designed eight different vibrotactile patterns, see figure 3.4, which are distinguishable and as further experiments have shown adequate for a navigational aid. Five

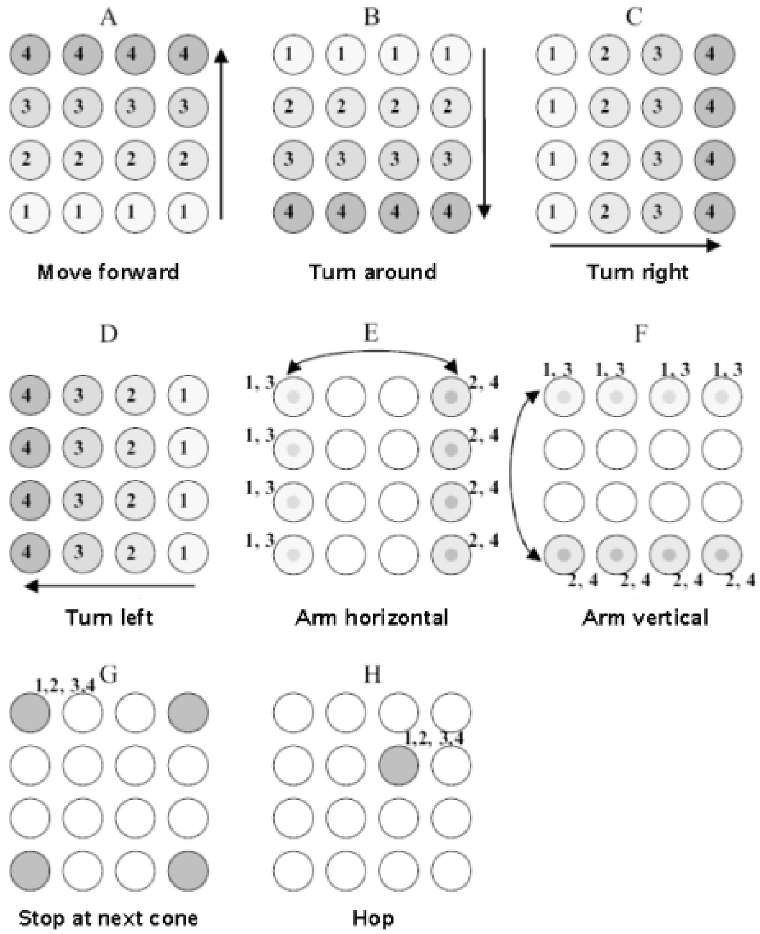


Figure 3.4: Vibrotactile patterns presented to the torso as directional cues [Jones et al., 2006]

of the patterns (A, B, C, D, G) indicate a direction of movement like move forward, turn around, turn right, or turn left, while the remaining three patterns (E, F, H) are associated with body movements that the subject is required to

perform like raise arm horizontally, raise arm vertically, or hop.
The tactile display on the back also proved to be able to communicate military arm and hand signals [Jones et al., 2007]. In this vibrotactile system the location of stimulation, the relative duration of the signals, and the number of vibration motors concurrently active are effective to communicate information. In previous tests they have shown that the ability to recognize vibrotactile patterns is superior on the back in comparison to the forearm [Piateski and Jones, 2005], were based on the smaller skin surface a three-by-three array tactile display was used.

3.3 Tactile Feedback in Mobile Phone Applications

In general tactile feedback in mobile phones is very simple. In silent modus, for example, vibrations or simple buzzes, indicate an incoming call or text message. This type of application does not fully exhaust the potential of tactile feedback for communication. A selection of applications that make use of more complex tactile feedback is presented in the following. These applications benefit from the qualities of tactile feedback in mobile applications for communicating information discretely without disturbing others and being especially appropriate in noisy environment.

Vibrotactile messages for mobile phone alerts

Brown and Kaaresoja [2006] developed a set of distinguishable vibrotactile messages, Tactons, to represent mobile phone alerts. These Tactons use only those parameters that standard mobile phone vibration motors support. They showed that the Tacton recognition rate is comparable to those designed for a high specification transducer [Brown et al., 2005]. With high specification transducer it is possible to vary all tactile parameters.
In each Tacton two pieces of information were encoded: the type of alert (voice call, text message, or multimedia message) and the priority of the alert (low, medium, or high). The type of alert is presented in rhythm, while the priority of the alert is presented by the intensity of the vibration stimuli. During the study users held the mobile phone in

their hand.
To improve the recognition rate gained in previous work, Brown et al. [2006] investigate an approach with multidimensional Tactons for non-visual information presentation in mobile devices. In this work a high specification transducer, the C2-Tactor, is used. Tactons were designed to represent alerts which remind the user of upcoming events. The type of the appointment is encoded in rhythm, the importance of the appointment in roughness, and the time remaining until the appointment is encoded in the location of the vibration on the users forearm.
The results of the investigation show that keeping the number of Tactons low (up to 10) is necessary to achieve nearly perfect performance.

Improving touchscreen keyboard interactions

Another approach for enhancing mobile interactions is pursued by Brewster et al. [2007]. They add a vibrotactile actuator to a PDA and therefore improved touchscreen keyboard interactions. With the tactile feedback the PDA regains some of the feeling, which is lost, when interacting on a touchscreen with a finger [Hoggan et al., 2008]. In their study they use two different stimuli, which indicate the user a successful button press or an error. The results show that users enter significantly more text, make fewer errors, and correct more of the errors when tactile feedback is added.
Further investigations by Hoggan et al. [2008] suggest that using either the built in vibrotactile actuator or more specialized actuators, as e.g. used by Brewster et al. [2007], improves the usability of touchscreen keyboards.

Different approaches with piezoelectric actuators [Pasquero et al., 2007] for enhancing mobile interactions exist, but those stretch the skin of a finger to transmit information. As we are interested in vibrotactile feedback we will not examine them.

3.4 Tactile User Interfaces

The importance of computers in our daily live as well as at work increases more and more. Through help of tactile feedback it is possible to enhance user interfaces by offloading other senses and improving performance [Brewster and King, 2005]. In the following we present two ways for enhancing user interfaces through tactile feedback.

Haptic instant messaging (HIM)

Rovers and van Essen [2004] introduced a haptic enabled instant messaging framework, the Haptic Instant Messaging (HIM) framework, which combines communication of textual messages with haptic effects and hapticons. Hapticons consist of vibration patterns, which represent the haptic counterpart to emoticons used in instant messaging for expression of emotions and feelings. One way to display these hapticons to the user is the FootIO prototype also developed by Rovers and van Essen [2005].

InTouch

In a similar way Brave and Dahley [1997] developed the system InTouch, which is a medium for haptic interpersonal communication. It provides a physical link between users separated by distance. Instead of using vibrations, InTouch consists of three cylindrical rollers mounted on a base for each user. When one users rotates one of the rollers, the corresponding roller on the remote InTouch rotates in the same way.

Progress bar with tactile feedback

Brewster and King [2005] pursue another direction to enhance user interfaces. They present an investigation on the use of Tactons to present progress information. They suggest that sharing tasks between different senses allows better interaction. Therefore a progress bar with tactile feedback is enabled in which progress is encoded into a series of vibrotactile impulses. This allows the user to visually pay attention to the primary task, whilst monitoring the progress of the background task.

Other applications for improving human-computer interaction for mobile applications were already given in 3.3—"Tactile Feedback in Mobile Phone Applications".

3.5 Monitoring Postures in Sport and Daily Activities

In this section we present two different areas of research. On the one hand we want to introduce sport domains or domains of daily activities, where researchers deal with the monitoring of body postures and movements to improve performance. These applications make use of visual or auditory feedback, but presenting the information by tactile feedback would be appropriate. On the other hand we want to present domains where tactile feedback is already in use. All of these domains could help us in finding new domains where tactile feedback for correcting posture in physical activities might be beneficial.

Monitoring Movements

Kunze et al. [2006] studied the monitoring of Thai-Chi movements with the help of different sensors and concluded that a automated evaluation of Thai Chi is possible. Kwon and Gross [2005] went a step further and developed a motion training system for martial arts, which generates visual feedback. An example of the visual feedback given by the motion training system is pictured in figure 3.5.

(a) (b) (c) (d)

Figure 3.5: Example of the visual feedback used by Kwon and Gross [2005] motion training system

Monitoring seated posture

Another application, where visual feedback is proposed, is a system by Dunne et al. [2007] for monitoring seated posture of computer users. Through sensor integrated into the garment the seated posture of the user is monitored. The actual posture can be observed by a system tray icon interface. The system tray icon is a colored circle, with a white outline of a seated stick-figure. As the user passes from healthy over warning to unhealthy seated posture, the icon changes its color from green over yellow to red and in the same way the stick-figure changes. In this system the user does not have its primary attention to its seating posture, but can control his posture by a look at the system tray or will be warned if his posture gets unhealthy by a popup warning message. Nevertheless, by looking to the system tray icon the user's visual locus of attention is changed from its primary task to a secondary. When using tactile feedback instead of visual feedback the user does not has to change his locus of attention.

Instead of using visual feedback Insight Ltd.[2] uses real-time audio feedback in their iTrainer^{TM} Golf to inform the user how to improve his golf swing.

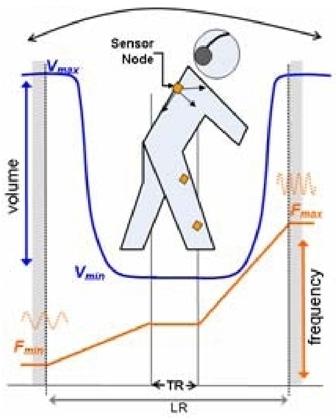
Another system that makes use of audio feedback is the Biofeedback Wireless Wearable System (Bio-WWS) developed by Brunelli et al. [2006]. This system detects a human's posture and gives audio feedback to help optimizing balance, e.g., to support the rehabilitation of patients that have lost their sense of balance. While a change in the users balance results in a change of the different parameters of the audio feedback like frequency, amplitude, and sound balance were adapted/modulated (see figure 3.6). This approach is similar to that used by Paradiso et al. [2004] and their Gait Shoe, which uses audio feedback to help users monitor their gait. When gait defects are discovered, the music becomes less melodic and strongly rhythmic. This change indicates the user his undesirable gait.

Biofeedback Wireless Wearable System (Bio-WWS)

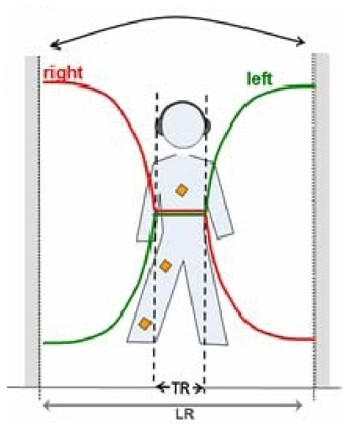
The use of auditory feedback has drawbacks that have been discussed in 2.1.2—"Auditory Feedback". One drawback is that by wearing headphones sounds of the environment are blocked out, which is not always appropriate especially in road traffic. Using tactile feedback instead of auditory will eliminate this drawback.

The investigations of Nakamura et al. [2005] include vibrotactile feedback. They help beginners to learn the basic of dances by a multimodal presentation method using visual and vibrotactile cues. The vibrotactile cues, released at the

[2] http://www.insight-sports.com



(a) Forward-Backward direction



(b) Left-Right direction

Figure 3.6: Audio feedback modulations for keeping balance [Brunelli et al., 2006]

wrists in this approach, indicate the action starting-timing of dance motions.

Physical therapy

For physical therapy Lindeman et al. [2006a] designed the TactaPack a wireless sensor/actuator package. The TactaPack warns the patient when performing a movement that will injury a joint recently operated by a vibrational stimulus. The stimulus is activated at the location of violation to "nudge" the patient back into the proper movement range. In coding severity of violation in intensity of vibration and providing vibration at the point of location, vibrational cues provide both temporal and spatial information.

All this applications show that tactile feedback can support users in performing daily or sport activities in the right way and therefore helps to improve the performance as well as helps the user to avoid unhealthy situations.

At our chair work has begun on a real-time snowboard training system [Spelmezan and Borchers, 2008]. Due to spatial separation on the slope, a snowboarding instructor often cannot talk to students when they perform exercises incorrectly. The feedback about this incorrectly performed exercises can only given with a delay. Therefore a system is developed to detect mistakes during the ride. Concurrently with this thesis, where we concentrate on new domains and a tactile language, tactile feedback is developed for the snowboard training system.

3.6 Tactile Languages

In this section we want to focus on different languages that have been developed in the context of tactile feedback.
We are interested in languages as they do not only provide the basic elements of feedback, but do also contain a structure to construct more complex elements. New "words" result from the composition of basic building blocks in an arbitrary way and according to certain rules. By building a tactile language it is possible to build a consistent set of tactile patterns. Therefore we will have in the following a closer look at tactile languages.

Tactile language

Different approaches exist for building tactile languages. One approach is to encode the alphabet tactilely to make written text accessible to visually impaired people (Braille) or to transmit messages fast over long distances (Morse code).
For visual impaired people Braille is of essential importance. Through this language visually impaired people are able to read text that will otherwise be refused to them because of their visual impairment. In Braille each letter has a pictorial presentation consisting of six dot positions, arranged in a rectangle containing two columns of three dots each. The letters differ from each other through the position and number of raised dots.
The International Morse code is one type of a alphabet which allows to transmit information over a long distance by coding single letters in short or long visual, auditive, or tactile signals.

Translate written text to tactile cues

Geldard [1957] designed two different tactile languages: vibratese and optohapt. With those languages it is possible to translate written text to tactile cues.
The first language, vibratese, uses five different locations

at the chest for delivering tactile cues. Through varying three intensities, three durations, and activating one vibration motor at the previously noted five locations a vibratory communication system is built (see figure 3.7). Letters and numbers were assigned to unique patterns, with the most frequently occurring symbols assigned to the shortest signals. Additional vibratory patterns were implemented for words which occur very often, like “the”, “of”, “and”, and “in”.

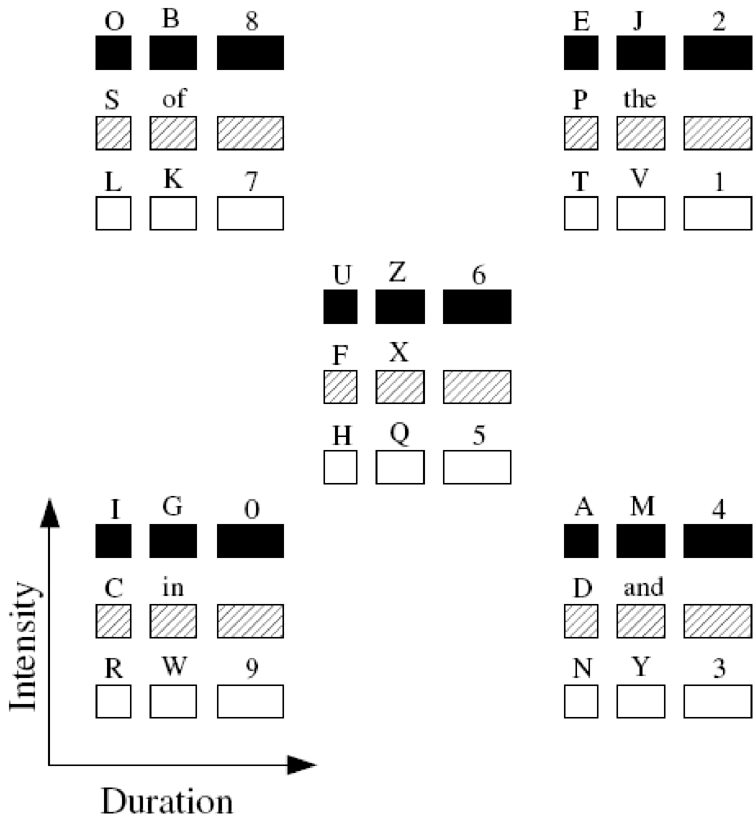


Figure 3.7: Coding of the vibratese language.
Each group of nine symbols belongs to a single vibration motor that varies in intensity and duration [Geldard, 1957].

The second language uses the optohapt [Geldard, 1966] a device which converts printed or typed characters into tactile signals (see figure 3.8). The tactile signals are triggered at nine vibration motors widely distributed across the body surface (see figure 3.8). The optohapt consists of a vertical array of nine sensors that scan horizontally across the written text at a constant speed. When a sensor scans over a black area of a printed character, the corresponding vibrotactile actuator stimulates the skin. Because the alphabetic characters have similar appearance they were first converted to more distinguishable symbols before scanning.

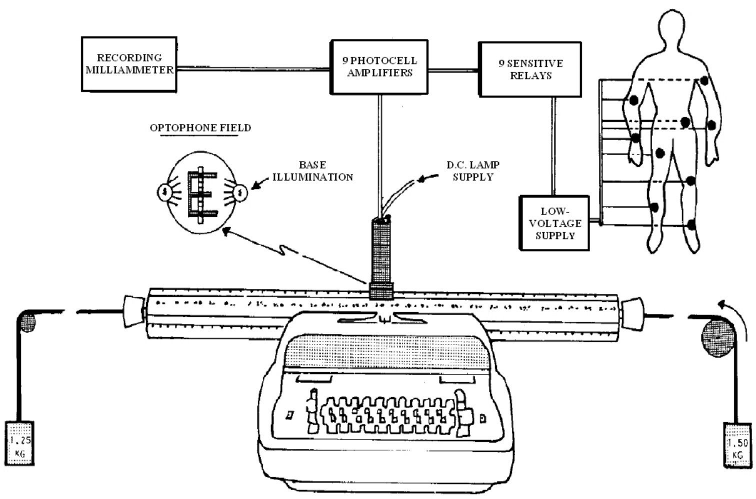


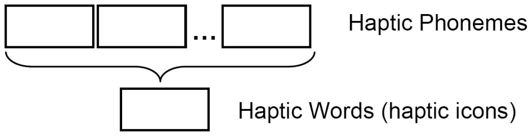
Figure 3.8: The Optohapt System [Geldard, 1966]

Another idea makes use of a more abstract approach for building tactile languages. Instead of using tactile alphabetic character this approach uses phonemes, which are the smallest distinctive segment of a language [Meyer, 2005]. These tactile languages do not only transmit speech through tactile cues, but are also able to transmit more abstract information.

Phoneme

Enriquez et al. [2006] explore the design of haptic phonemes as basic building blocks of haptic communication. They define a haptic phoneme as the smallest unit of a constructed haptic signal to which a meaning can be assigned. With the combination of these haptic phonemes serially (concatenation) or in parallel (superposition) haptic words, or haptic icons, are formed (see figure 3.9).

Haptic phonemes are constructed of simple waveforms (triangle, morph, square) with a fixed frequency and ampli-



(a) Forward-Backward direction

Figure 3.9: Buidling haptic words through concatenation [Enriquez et al., 2006]

tude (7Hz, 10Hz, 18Hz) presented through a haptic display, a haptically enabled knob. Because phonemes are the basic building blocks they have to be differentiable, identifiable, and learnable.
Through a user test it is determined that users can consistently recall an arbitrary association between a haptic stimulus and its assigned arbitrary meaning in a 9-phoneme set.

Further investigations in Tacton design were carried out by Brewster and Brown [2004a]. They give examples how the basic parameters for Tactons can be designed to convey information. One-element Tactons, which are comparable to the previously introduced haptic phonemes, can be combined to create compound, hierarchical, or transformational Tactons. Each one-element Tacton encodes only one piece of information. By combining these one-element Tactons more information can be expressed.

One-element Tactons

Compound patterns are assembled Tactons. The Tacton "create file" is assembled of the one-element Tacton "create" and the one-element Tacton "file". To build the compound Tacton "create file" the one-element Tactons are triggered successively.

Compound Tactons

Hierarchical Tactons use inheritance in their creation. Each Tacton is a node in a tree that inherits properties from the level above and adds more properties to it. Compound patterns can be used to add further levels in the hierarchy of Tactons.

Hierarchical Tactons

The third type of Tactons are transformational Tactons, which have several properties, each represented by a different tactile parameters. As an example the file type can be represented by rhythm, the size by frequency, and creation date by body location. Files of the same type, with the same size, but created at different dates will have the

Transformational Tactons

same rhythm and frequency, but will be triggered at different body locations.

One application for tactile feedback is “Cutaneous Grooves”, which is a coupling of haptics technology and music introduced by Gunther et al. [2002]. Instead of encoding specific information, they make use of the sense of touch to create an aesthetically pleasing experience. As sound is vibration, music is transmitted to the skin by vibration stimuli. They propose a compositional language for the sense of touch to accompany and enhance musical performances. Throughout a composition, vibrotactile stimuli are presented to thirteen different locations on the body with variations in intensity, duration, waveform and frequency. The musical structured spatio-temporal patterns of vibration are designed in the same manner as music as those are very similar, although the skins resolution is worse.

Cutaneous Grooves

3.7 Discussion

This chapter has reviewed the different applications where tactile feedback is used or might be beneficial. In the context of this thesis the reviewed work can be used to identify new domains where tactile feedback can be used and how this feedback has to be designed.

As the review shows a lot of work is done in the field of sensory substitution, providing navigational information, enhancement of mobile phone applications, and tactile user interfaces.
Further investigations are required in the field of daily and sport activities where we will focus on. There are already investigations in monitoring the user's body posture and giving feedback to the user, but some domains are very specific like those of Kunze et al. [2006] and Kwon and Gross [2005] who concentrate on martial arts. We want to focus on more general applications. Designing feedback for those domains will provide the possibility to design universal feedback patterns, which can be applied to a broader field of applications.

Investigations required in the field of daily and sport activities

In cases where tactile feedback is already in use for sport activities the tactile patterns are always quite simple [Nakamura et al., 2005, Lindeman et al., 2006a]. As the information increases, tactile feedback needs to make use of different tactile parameters to encode this information.

Tactile parameters

The related work identifies which tactile parameters have been used in order to design a distinguishable set of tactile patterns and which combinations. Table 3.1 gives an overview of the introduced related work, the tactile parameters, and the body locations that are used. The tactile parameters body location, rhythm and duration are most frequently used.

A structure how the different patterns can be designed in a consistent way is provided by a language. The previously introduced tactile languages will inform our own design of a universal and consistent tactile language for movement instructions.

Author	Tactile Parameters						Location	Application
	Frequency	Amplitude	Waveform	Duration	Rhythm	Body Location		
[Cardin et al., 2006]	X					X	Torso	Collision Detection
[Bloomfield and Badler, 2007]						X	Arm	Collision Detection
[Schätzle et al., 2006]						X	Arm	Collision Detection
[Ross and Blasch, 2000]					X	X	Shoulder	Situation Awareness
[Lindeman et al., 2006b]						X	Torso	Situation Awareness
[Cassinelli et al., 2006]						X	Head	Situation Awareness
[Rupert, 2000]						X	Torso	Situation Awareness
[Tsukada and Yasumura, 2004]				X	X	X	Torso	Navigation
[Bosman et al., 2003]				X		X	Wrist	Navigation
[van Erp and van Veen, 2001]						X	Legs	Navigation
[Tan and Pentland, 2005]				X		X	Torso	Navigation
[Jones et al., 2006]				X		X	Legs	Navigation
[Brown et al., 2006]		X			X		Hand	Mobile Application
[Brown and Kaaresoja, 2006]					X	X	Arm	Mobile Application
[Brewster et al., 2007]		X					Hand	Mobile Application
[Rovers and van Essen, 2005]								Tactile User Interface
[Brewster and Brown, 2004a]		X		X	X		Wrist	Tactile User Interface
[Raisamo et al., 2007]					X		Hands	Memory Game
[Nakamura et al., 2005]						X	Wrist	Sport Activity
[Rovers and van Essen, 2005]		X				X	Full-Body	Physical Therapy
[Geldard, 1957]		X		X		X	Torso	Tactile Language
[Geldard, 1966]						X	Full-Body	Tactile Language
[Enriquez et al., 2006]		X	X				Hand	Tactile Language
[Brewster and Brown, 2004b]	X				X	X		Tactile Language

Table 3.1: Overview of Related Work

Chapter 4

Designing the Tactile Feedback Patterns

"Design is directed toward human beings. To design is to solve human problems by identifying them and executing the best solution."

— Ivan Chermayeff

After we have reviewed the use of tactile feedback in different applications, we want to describe the design of our tactile patterns.

As the chapter 3—"Related work" has shown there is a lot of research done in tactile feedback, but in some domains there is still a need for further investigations like in the domains of daily and sport activities. Although there are already approaches for specific domains in this field (c.f. 3.5—"Monitoring Postures in Sport and Daily Activities"), a general approach was not explored.

In the following we want to find new domains in the field of daily and sport activities from which we can derive typical movements to develop universal patterns for those. To design tactile patterns we first have to decide which tactile parameters are appropriate. As support for developing a consistent, distinguishable set of tactile patterns for movement instructions we define a structure of a tactile language on which we will base the design. Through this structure we will design a first set of tactile patterns for movement instructions.

Finally in the last section of this chapter we will present the decisions we made concerning the wearable design.
In the following chapter 5—"Evaluation of the Designed Patterns" the designed patterns will be tested regarding their intuitivity, learnability and universality. Due to this evaluation of the tactile patterns further modification or re-design of the tactile patterns will be carried out.

4.1 New Domains for Tactile Feedback

New domains aside from the snowboarding project [Spelmezan and Borchers, 2008] for full-body tactile feedback can be found in everyday live and in several sport domains.

Back pain a widespread disease

80% of the german population complains about back problems and 30% of all sick certificates are alloted to diseases of the locomotor and postural apparatus [BAuA, 2008]. These diseases are evoked by incorrect sitting postures and incorrect postures while lifting heavy objects.
Practicing sports can improve the overall state of health, but the positive effects of doing so can be abolished by a false posture or false course of movements. Furthermore the right sequence of movements is necessary to control the situation and to avoid injuries.

Vibrotactile feedback will avoid false posture

Through the vibrotactile feedback the user will be encouraged to perform daily and sport activities in the right way. Subsequently we introduce those domains which build the basis for our design of tactile movement instructions.

4.1.1 Sedentary Work

From childhood on one is trained to sit upright with straight shoulders, but only few have internalized it. While we are sitting at the table or on the sofa, we are bending

our back because it is more comfortable instead of sitting upright.
This problem was previously addressed by Dunne et al. [2007]. In their work the seated posture of computer users is monitored by a wearable plastic optical fiber sensor and give visual feedback over a system tray icon, which changes color from green over yellow to red when the user adopts a unhealthy sitting posture.

Improving seated posture

Instead of visual feedback we will give the user tactile feedback, so the user does not have to shift his visual locus of attention [Raskin, 2000] from his primary task to the system tray to monitor his body posture. This type of feedback will be especially beneficial for bus drivers and truck drivers who are bound to their seat the whole day and want to avoid consequential injuries by unhealthy sitting postures. While they keep their visual locus of attention to the traffic, they perceive haptic feedback that will support them in maintaining a healthy sitting posture.

In a healthy sitting posture one has to sit upright, with a straight spine, straight shoulders, thigh and shank in a right angle, and the sole of the feet resting completely on the floor. In this thesis we will concentrate on the straight spine and the upright sitting posture.

4.1.2 Carrying Heavy Goods

Through everyday life one has sometimes to lift and carry heavy objects like, e.g., watertanks. Furthermore in some businesses it is required to carry heavy stocks the whole day. Nurses have to heave patients into their bed or from one bed to another after an operation. Warehousemen and craftsmen also have to carry heavy stocks. Especially in these businesses it is essential to maintain an adequate body posture to avoid consequential injuries of the intervertebral disks and knee-joints.

When picking up heavy stocks it is necessary to keep the back upright while bending the knees. This posture disburdens the spine and equally distributes the weight of the stock. People tend to keep their knees straight and to bend their back instead when picking up the object as is illus-

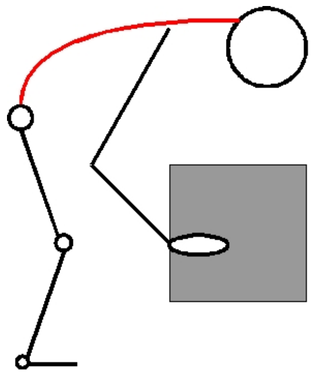


Figure 4.1: Load on the spine while carrying heavy goods

trated in figure 4.1.

4.1.3 Horse Riding

During horse riding lectures the trainer is not able to physically interact with the learner. The learner is dependent on the vocal feedback of the trainer. In contrast to vocal instructions tactile instructions do not only indicate that the body posture has to be correct but also where. Another problem concerning vocal orders is that they can be missed in situations where more than one horse rider is on the indoor or outdoor riding ring. To overcome the low audibility the trainer can give the learner vocal orders via a headset.

In most cases though the beginner will mostly learn on their own, so it would beneficial to introduce a technique that is capable of giving the learners continuously feedback regarding their current body posture. Thereby body posture mistakes will not creep in and the learning progress will be improved.
Another important aspect is that advanced riders pay more attention to the horse and the variation of track figures. Track figures are figures performed in a riding arena, usually for training purposes. While doing so they do not think about their own riding posture. A system that reminds them to improve their posture would be beneficial.

In the dressage sport the following dressage seat is defined. The rider is sitting upright with head, shoulder, hip and heel building a straight line. The heel is the deepest point and the weight is equally distributed.

Horse riding learners tend to lean their upper body forward or backward instead of keeping it upright. Furthermore they often bend their shoulders forward. Another typical error is to sit left or right leaning in the saddle. Especially when the horse is to walk the circle horse riders tend to buckle their upper body to the center of the circle.
In addition learners often bend their legs as if they are sitting on a chair. The legs should be kept in tight contact to the horse in order to give aids to the horse effectively, but learners often tend to point with their toes outwards. Another way to give aids to the horse is performed by using the reins. Instead of pointing the thumbs upwards learners tend towards pointing them forward.
In the following we will concentrate on body postures of the legs and upper body and neglect for example the posture of the hands or feet.

4.1.4 Nordic Walking

Nordic walking has become a popular sport that many people practice to improve their overall state of health. The positive effects of nordic walking will be abolished by a false course of movements.
While practicing nordic walking the upper body has to be straight. As during normal walking activity the arms and legs have to swing antiparallel. The hands have to be opened and the pole has to be released after each pole strike. Each pole strike has to end slightly behind the line of the pelvis.
Wrong postures include leaning and tilting the upper body too far, having a permanent fist or having the hand permanently open, a wrong pole position, or moving arms and legs of one side in parallel.

4.1.5 Typical Movements Identified as Universal

Each of the previously introduced domains has a specific body posture, but they are related to each other. Therefore we point out which are the commonalities and develop tactile feedback that will indicate a wrong posture. The right execution of each movement required in each domain is necessary to avoid injuries as well as postural deformities. Furthermore in sport domains it helps to improve the learning progress as frequent concurrent feedback might be beneficial for learning new motor skills [Wulf, 2007]. Further investigations in this field are required.

Common movements

On the one hand we want to concentrate on movements that all presented domains have in common, but we are also interested in special movements. These special movements only occur in a few or one of the presented domains. Together with tactile feedback for special movements it is possible to use our designed feedback in a widespread field of domains. Furthermore the collection of common movements will support the attempt to design a tactile language for movement instruction. With the specific movements it is possible to test if the tactile language is also usable for those.

One widespread false posture is to have a bended back. A bended back is not appropriate while carrying stocks, sitting or practicing sport activities in general. Other typical errors concerning the upper body are to lean the upper body too far in any direction or to bend shoulders forward. These upper body posture mistakes are common in all previously described domains. Another motion sequence we want to present by tactile feedback is to swing the arms antiparallel, although this kind of body movement error only occurs in one of the previously presented domains. In addition to signalizing to lean the upper body in any direction, keeping the shoulders straight, and swinging the arms, we also want to find a tactile feedback pattern to turn the upper body.

Other universal body posture errors affect the legs. While heaving objects it is necessary to bend the knees and keeping the upper body straight to disburden the spine and dis-

Lean upper body forward Lean upper body to the left	LF LL	vs. vs.	LB LR	Lean upper body backward Lean upper body to the right
Take shoulders backward	TS			
Swing left arm forward and right arm backward	SLA	vs.	SRA	Swing right arm forward and left arm backward
Turn to the left Bend the legs Shift weight left	TL BL SWL	vs. vs. vs.	TR SL SWR	Turn to the right Straighten the legs Shift weight right

Table 4.1: Summary of movements which are common in various activities

tribute the weight equally. Bending or straightening the legs is one movement instruction we want to give. Another one is to shift the weight to the left or right, which is also needed to distributed the weight equally.

Countermovements

Each of the previously presented body posture errors will be indicated by tactile movement instructions, which inform the user how to move the body correctly. All of this movements are common in daily physical activities and in sport domains. Except for one, all of these movements do have a corresponding countermovement. The thirteen movements we choose to focus on within this thesis are listed below, see table 4.1.

4.2 Tactile Design

Physical feedback

To assist users in the course of movements they have to perform in different domains, we decided to use tactile feedback. The advantages of tactile feedback over other senses is described in the previous chapters. These advantages are amongst others the physical nature of tactile feedback and the quality to support or complement other senses.

For the design of the tactile feedback patterns we have to decide which tactile parameters are appropriate for our usage. The tactile parameters duration and body location seem to be appropriate as they are easy to distinguish by the tactile sense [Jones et al., 2007, Brown, 2007]. These two parameters have also been used for tactile navigation aid systems, as shown in chapter 3.2—"Tactile Feedback for

Navigation" for comparison. Furthermore these tactile parameters are two of the primary and independent parameters of vibratory cutaneous stimulation as Geldard [1957] stated.

People more likely confound tactile patterns that share the same actuators than patterns that use distinct actuators for each command [Geldard and Sherrick, 1965]. To elude this cause for confounding patterns we will design full-body tactile feedback.

Full-body feedback

Two different approaches are deviated from the related work how tactile directional cues can be interpreted. The one approach adopts the ideas of common body language, where a hand is used to push a person in the correct position. This idea was also used by Lindeman et al. [2006a] to nudge the patient back into a proper, healthy posture and Gemperle et al. [2001] to guide a person in the correct direction. We will call this approach "push"-metaphor. The other approach instead, which is used by Bosman et al. [2003] and Ross and Blasch [2000], indicates the direction by a vibration on this particular side. This approach is called "push"-metaphor.
In the following the push-metaphor, similar to Lindeman et al. [2006a], is used, because no guideline exist which of the two metaphors have to be used to give tactile feedback.

Push- vs. Pull-Metaphor

With the help of sensory saltation it is possible to design spatio-temporal patterns which "draw" directional lines on the user's skin. Tactile applications that make use of this for navigational cue are reviewed in chapter 3.2—"Tactile Feedback for Navigation".

The designed tactile patterns should be as simple as the visual symbology in navigation systems, where information is only presented when a course change is necessary [van Erp and van Veen, 2001]. If no tactile message is presented the body posture is correct.

4.2.1 Body Locations

There are a lot of possible actuator positions over the whole body. Not all of those are appropriate or are already engaged. Evaluating the different body locations by a user test helps to decide which of these are appropriate or if other body locations have to be used.

To transmit directional information by tactile feedback most often the torso is used [Cardin et al., 2006, Ross and Blasch, 2000, Tsukada and Yasumura, 2004, Rupert, 2000, Lindeman et al., 2006a, Tan and Pentland, 1997, Jones et al., 2006], but also other body locations are used like the wrists [Bosman et al., 2003], shoulder [Ross and Blasch, 2000], arms [Bloomfield and Badler, 2007, Schätzle et al., 2006], and the legs [Erp and Veen, 2004].
The approach of Lindeman et al. [2006b], where the stimulus is triggered directly at the affected body part is of special interest. We aim to design feedback for movement instructions that concern each part of the body. Therefore the tactile feedback should be activated at the part where the body posture correction is needed respectively.

Feedback on the body part that needs correction

In figure 4.2 the body locations for the actuators are shown, which we have chosen. Their appropriateness will be approved in a user test.

Vibration Motor Spacing

The spacing between the vibrations motors is determined by the two-point threshold (see 2.1.3—"Tactile Sensation and Perception") and guidelines for sensory saltation [Tan et al., 2000]. In figure 4.2 the position of each vibration motor is pictured together with the designation of the body location. In table 4.2 the abbreviations are explained.
To facilitate the use of sensory saltation the motors are arranged in lines at different body location which provide enough place. On the upper body we placed three motors in a line on the front (FMB), side (LLB and LRB), and back (BMB) with a gap of 10 cm between each vibration motor on front and back and with a gap of 4,5 cm on the side respectively. On each collarbone (CB) and on the side of the

upper arm (LRA, LLA) we placed one motor. Two more motors are on the front and back of the upper arms (FLA, FRA, BLA, BRA). On the front (FLT, FRT), side (LLT, LRT), and back (BLT, BRT) of the thighs there are three vibration motors in a line with a gap of 6cm between each. Furthermore there is one motor in the palm (LP, RP) as well as in the sole of foot (LSF, RSF) and ball of the foot (LBF, RBF).

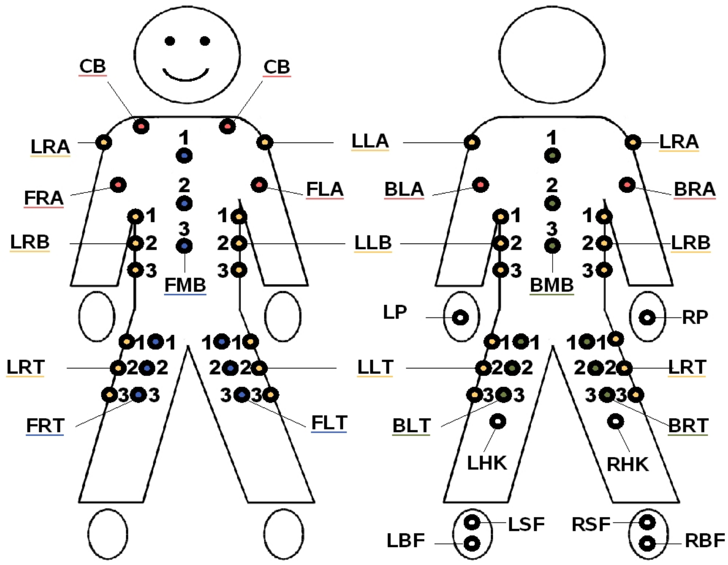


Figure 4.2: Position of the vibration motors

Perception of Vibration on Different Parts of the Body

Appropriateness of different body locations

Although there is data in the literature how people perceive vibration, we carry out a user test to measure when people perceive the vibration of our vibration motors on different parts of the body, which are not necessarily mentioned in literature before. In this test it is on the one hand explored if all selected body locations are appropriate or if alternative body locations should be used. On the other hand it is explored if the vibration frequency need to be calibrated for different body locations.

Subjects
In the user test three male and six female subjects partici-

CB	Front Shoulder
LRA	Lateral right arm
LLA	Lateral left arm
FRA	Front right arm
FLA	Front left arm
BRA	Back right arm
BLA	Back left arm
LRB	Lateral right body
LLB	Lateral left body
FMB	Front middle body
BMB	Back middle body
LP	Left Palm
RP	Right Palm
LRT	Lateral right thigh
LLT	Lateral left thigh
FRT	Front right thigh
FLT	Front left thigh
BLT	Back left thigh
BRT	Back right thigh
LHK	Left hollow of the knee
RHK	Right hollow of the knee
LBF	Left ball of the foot
LSF	Left sole of foot
RBF	Right ball of the foot
RSF	Right sole of foot

Table 4.2: Abbreviations for different body locations

pate in the age between 20 and 53 years. Each subject wears a jeans and a standard t-shirt during the test. All subjects are right handed and have no diseases that can influence the perception. Subjects do not have prior experience with tactile feedback except the mobile phone vibration alarm.

Procedure
The vibration motors are attached to the clothes of the subjects by hook-and-loop stripes (cf. 4.2.6—"Garment Design"). We test all illustrated positions, except the lateral position of the arms. To reduce the user test duration we limit the tested body parts to the right side. The test lasts approximately one hour.

For each position on the body we measure the lower threshold when the user perceives the vibration first and the upper threshold, which is the highest frequency of the vibrational motors that can be tolerated. Finally we let the user judge the different positions on a scale between 1-5 (1 = pleasant up to 5 = unpleasant).
The tested positions on the body are determined through the different domains and the kind of false posture in the different domains, c.f. figure 4.2 for comparison.

The vibration frequency is controlled by PWM signals, which are increased in steps of five, starting at 0 PWM. The maximum possible PWM signal is 255 PWM at approximately 4V (about 180 Hz).

Results
The vibration motors for each body location shown in figure 4.2 are numbered. The top most is motor 1, the next is motor 2, and the lowest at the corresponding body location motor 3. The determined minimum average PWM signal given is 22,86 PWM, which is around 65 Hz. The standard deviation is low (7 PWM).

The standard deviation measured for the maximum given PWM signals is approximately 91 PWM, which results from a few outliers of the participants that are on the one hand very sensitive or on the other hand insensitive. The maximum given PWM signal of the latter is always 255 PWM. The determined average maximum PWM given is 148,52 PWM, which is around 160 Hz (cf. figure 2.9). In figure 4.3 the average maximum PWM signal for each body location is shown.

The rating of the different motor locations concerning their pleasantness is shown in figure 4.4. Vibration motors in the hollow of the knee (LHK) or near by (FLT3 and BLT3) are worse rated.

Discussion
The results show that the employed vibration motors are sufficient to give tactile feedback in the lab. If they are also sufficient in the field further explorations have to show. Participants first recognize vibrations with a frequency of 65 Hz. The low standard deviation demonstrates that this

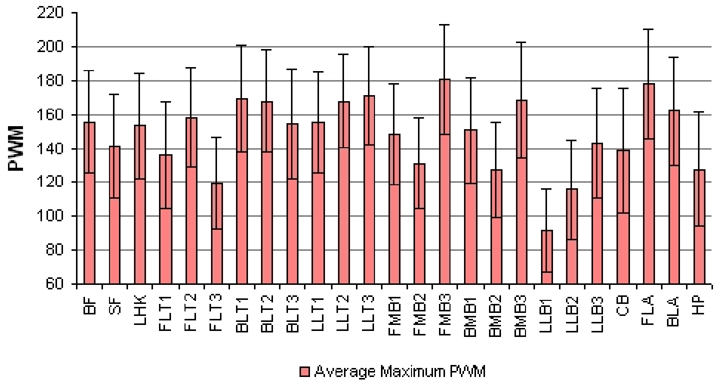
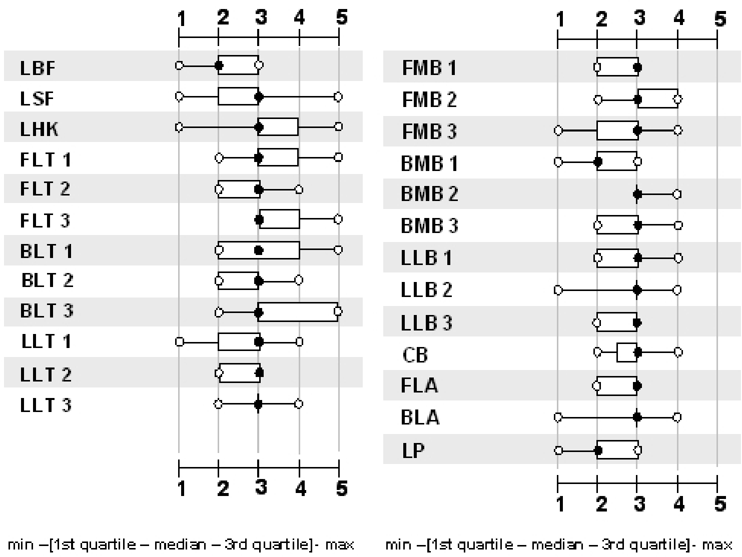


Figure 4.3: The average maximum PWM signal that is given at different parts of the body (with standard error)



(a) lower body (b) upper body

Figure 4.4: Rating of the different motor locations concerning their pleasantness

is comparable for all participants.

The determined average maximum frequency of 160 Hz is below the maximum frequency our vibration motors can achieve (180 Hz). The high standard deviations indicates that the maximum given vibration frequency is variable between different participants in contrast to the minimum frequency. Therefore it could be beneficial to be able to calibrate the vibration frequency concerning different body locations. Nevertheless in the following the maximum frequency (180 Hz) is given to assure that everybody is able to perceive the vibration signal without a time consuming calibration.

In detail the results show that subjects are very sensitive at the lateral site of the torso, where the average maximum PWM is lower (116,85 PWM which equates 130 Hz) than the overall average.
Except the hollow of the knee all tested body locations can be used for the tactile design. Vibration at the hollow of the knee or near by are rated as being very uncomfortable so this body location will not be used.
Although subjects find the vibration in the palm of the hand very pleasant we will not use this location for motor positioning, because the hands should be kept free.
The motor positions under the feet will not be used, because wearing the vibration motors under the feet would be very uncomfortable when putting pressure on the feet. During the test subjects are sitting when the vibration motors are attached to the feet.

The problems that arise with using hook-and-loop stripes are discussed in 4.2.6—"Garment Design".

4.2.2 Duration of the Vibration Stimuli

The stimulus duration (SD) and interstimulus interval (ISI) are deviated from the sensory saltation phenomenon. To evoke sensory saltation the ISI can vary from about 20 to 300 ms, but with 50 ms being near optimal [Geldard, 1985]. The optimal number of pulses to be sent varies between three and six [Geldard and Sherrick, 1972]. We will use three pulses as it is also used in other directional displays [Tan and Pentland, 1997].
The duration and intensity of the pulses is of secondary importance [Geldard and Sherrick, 1972, Geldard, 1985]. In the following we will use a stimulus duration of 100ms.

Duration: SD = 100ms
ISI = 50ms

4.2.3 Frequency of the Vibration Stimuli

In 4.2.1—"Perception of Vibration on Different Parts of the Body" we determined a average frequency of 160 Hz, which is near the maximum frequency (approximately 180 Hz) which can be achieved by the used vibration motors. As the frequency changes with the amount of adhesive tape used to isolate the vibration motor and with the type of attachment to the garment, we will use the maximum frequency to assure good perception of the vibration. This frequency is close to the maximum stimulation of skin mechanoreceptors (250 Hz) [Verrillo and Gescheider, 1992] and similar to the vibration frequency of similar motors [Jones et al., 2004].

Frequency: 180 Hz

The benefits of variations in frequency and intensity respectively, which is used in [Lindeman et al., 2006a, van Erp and van Veen, 2001, Brown et al., 2006], will be postponed to future work.

4.2.4 Structure of the Tactile Language

Each body movement in daily activities and sport activities consists of basic movements that concern only a specific part of the body. Therefore it is possible to identify basic movements which are combined to more complex movements. While heaving goods it is for example important to bend the knees and keep the upper body straight to avoid injuries. This course of movement can be partitioned into two basic movements: bending the knees and keeping the upper body straight. Even the movement bending knees can be further separated in a movement of the left leg and the right leg.

Identify basic movements

With the development of unique tactile patterns for each basic movement we are able to combine them in an arbitrary way to obtain new complex movement instructions. This is like a language where you have basic building blocks, phonemes, which can be composed to create words and sentences. Because not all combinations that are possible are reasonable at the same time the respective appli-

Complex movement instructions

cation will determine the required constraints for possible combinations.
In horse riding, for example, both hands hold the reins in front of the body. A pattern for taking arms backwards will not be required.

The notation of the tactile design is partly based on the Tacton Design Principles [Brown, 2007, Brewster and Brown, 2004a]. Instead of using the term Tacton we will use the term tactile pattern or tactile movement instruction.
The basic movements are one-element patterns consisting of one vibration motor at a certain body location. We will use a notation for the one-element patterns that is of the form of $P^3(x_1)$. It means that motor 1, at the body location x, pulses three times. If the body location consists of only one vibration motor only the body location is mentioned.

One-element patterns

These simple patterns can be combined in various ways. One way is to simultaneously activate different vibration motors at different body locations. This way of combining one-element patterns is symbolized by $SP\_P^3(x1, x2) = P^3(x1) + P^3(x2)$ with x1 and x2 denoting vibration motors or body locations with only one actuator.

Simultaneous pattern

Another way is to combine one-element patterns to create compound patterns [Brewster and Brown, 2004a]. One example for a compound pattern is a pattern that evokes the sensory saltation phenomenon. Three motors in a line are successively activated. First of all motor 1 vibrates three times $P^3(x_1)$, then motor 2 also vibrates three times $P^3(x_2)$, and finally motor 3 vibrates three times $P^3(x_3)$. This compound pattern will be named in the following "rabbit" R with $R(x1, x2, x3) = P^3(x_1) \rightarrow P^3(x_2) \rightarrow P^3(x_3)$ with x denoting a body location. It is possible to create a rabbit which subscribes an upwards arrow (R_U), a downwards arrow (R_D), or a sidewards arrow (R_L or R_R). Instead of using the motor denotation it is also possible to only name the corresponding body location together with the direction of the activated rabbit pattern, for example $R_U(BMB)$ for $P^3(BMB_3) \rightarrow P^3(BMB_2) \rightarrow P^3(BMB_1)$.

Compound patterns

Rabbit pattern

Together with the one-element patterns the rabbit patterns build the basis for our tactile movement instructions. We will use two ways to combine these rabbit patterns. On the one hand it is again possible to compound rabbit patterns, which will be denoted by $CP\_R(x, y) = R(x) \rightarrow R(y)$ with x and y being body locations. On the other hand it is possible to activate rabbit patterns $SP\_R(x, y) = R(x) + R(y)$ simultaneously with x and y denoting body locations.

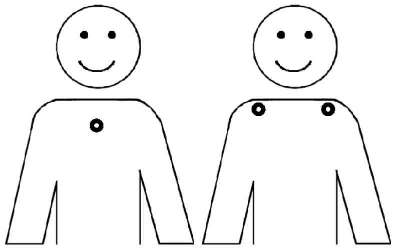
4.2.5 Tactile Movement Instructions

With this nomenclature we are able to describe our designed patterns. The figures 4.5, 4.6, 4.7, 4.8, and 4.9 below, shall illustrate the idea of the designed patterns. The different grayscales used for the vibration motors indicate different activation times. White filled motors are activated first, followed by darker grayscales. Vibration motors with the same color are activated at the same time. The arrows show the order in which compound patterns are activated like the direction of rabbit patterns.
As mentioned before, various combinations of tactile patterns are possible, when combining one-element, rabbit, compound, and simultaneous patterns, but not all are reasonable. The design is inspired by the different movements which are common in the previously introduced domains (see table 4.1).

First we describe which patterns we designed for the upper body. For each of the previously described pattern types different body locations are used. It is possible that the perception and associations of the pattern is dependent on the body location.

One-element patterns will be applied to the topmost vibration motor at the back of the body ($P^3(BMB_1)$, see figure (4.5 a), to the topmost actuator at the front of the body ($P^3(FMB_1)$), to the left lateral shoulder ($P^3(LLA)$), and to the right lateral shoulder ($P^3(LRA)$). We also designed simultaneous one-element patterns. In these patterns two vibration motors are activated concurrently. This happens at the shoulders ($SP\_P(CB)$, see figure 4.5), on the leading left arm and at the rear right arm simultaneously ($SP\_P(FLA, BRA)$), as well as on the leading right arm and rear left arm ($SP\_P(FRA, BLA)$).

Another type of patterns used at the upper body are rabbit patterns. Rabbit patterns are activated in upwards direc-



(a) one-element (b) simultaneous

Figure 4.5: Two types of one-element patterns

tion at the front of the body ($R_U(FMB)$, see 4.6 a), at the back of the body ($R_U(BMB)$), at the left lateral side of the body ($R_U(LLB)$) as well as at the right lateral side of the body ($R_U(LRB)$).

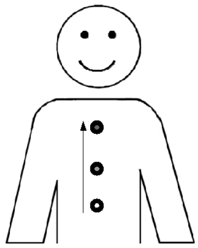


Figure 4.6: Rabbit pattern on the front of the torso in upwards direction

We also use the rabbit pattern horizontally by activating successively one motor at each body location around the chest. The sensory saltation phenomenon usually might not cross the body midline [Coleman, 2002] because of the left-right dichotomy. The left-right dichotomy occurs because the touch-sensitive nerve endings in the skin on each side of the body are connected to opposite hemispheres of the brain. This neurological gap can be bridged by placing vibration motors at the midline Tan et al. [2000]. Newer investigation of Tan and Pentland [2005] and Jones et al. [2006] have shown that sensory saltation also crosses the midline when the vibration motors are placed in the proximity of the spine. We will examine how such a rotation pattern will be perceived.

This rotation can occur clockwise ($R_R(FMB_2, LRB_1, BMB_2, LLB_1)$) or counterclockwise ($R_L(FMB_2, LLB_1, BMB_2, LRB_1)$, see figure 4.7 a).
On the basis of a pilot test we also use this pattern with two rotations to increase the rotation perception (($R_L(FMB_2, LLB_1, BMB_2, LRB_1))^2$, $(R_R(FMB_2, LRB_1, BMB_2, LLB_1))^2$). To assure that the duration of the whole pattern does not lengthen because of the two rotations around the upper body a decrease of the standard stimulus duration to 50 msec and inter-stimulus interval to 30msec is implemented.
The last rotation pattern is again a simultaneous rabbit pattern, here a simultaneous rotation pattern. The difference is, that at each time two of the three vibration motors at each body location vibrate. These rotations are again in clockwise ($R_R(FMB_{2+3}, LRB_{1+3}, BMB_{2+3}, LLB_{1+3})$) and counterclockwise direction ($R_R(FMB_{2+3}, LLB_{1+3}, BMB_{2+3}, LRB_{1+3})$, see figure 4.7 b). Other simultaneous rabbit patterns are used, but

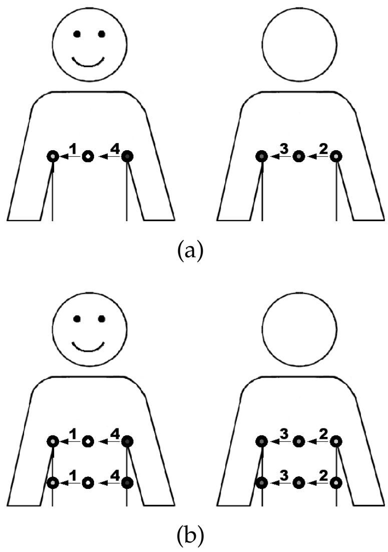
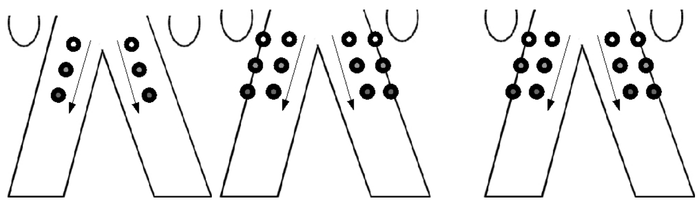


Figure 4.7: Rotational rabbit patterns on the torso

now in an upward direction. In the one rabbit patterns at the front and at the lateral are activated simultaneously ($SP\_R_U(FMB, LLB, LRB)$). In the other instead activating the rabbit pattern at the front it is activated at the back ($SP\_R_U(BMB, LLB, LRB)$).

For the movement instructions of the legs we designed different tactile patterns, which all make use of simultaneous rabbit patterns. These simultaneous rabbit patterns are applied to the front ($SP\_R(FMT)$), to the back ($SP\_R(BMT)$) of the legs, and all around of the thighs ($SP\_R(FMT, BMT, LLT, LRT)$), see figure 4.8). These rabbit patterns are either activated in upwards or downwards direction on the thighs.



(a) (b)

Figure 4.8: Simultaneous rabbit patterns on the thighs

Another pattern designed for the legs is a simultaneous rabbit pattern, which will be delivered to the lateral side of the thighs. These patterns are composed of an upward proceeding rabbit pattern on the one leg and a downward proceeding rabbit pattern on the other leg, which will either be $SP\_R_{UD}(LLT, LRT) = R_U(LLT) + R_D(LRT)$ (4.9 a) or $SP\_R_{UD}(LRT, LLT) = R_U(LRT) + R_D(LLT)$. Instead of combining these rabbit patterns simultaneously it is also possible to combine them successively to a compound rabbit pattern. This pattern starts either on the left lateral thigh and ends at the right lateral thigh $CP\_R_{UD}(LLT, LRT) = R_U(LLT) \rightarrow R_D(LRT)$ (see figure 4.9 b) or the other way around ($CP\_R_{UD}(LRT, LLT) = R_U(LRT) \rightarrow R_D(LLT)$) . To verify if the designed patterns are appropriate to indicate a body movement, user studies will be carried out. The test setup and the results will be described in chapter 5—"Evaluation of the Designed Patterns". An overview of all designed patterns is given with table 4.3.

First of all we examine what is intuitively associated with a given pattern, which movement somebody is incited to perform after perceiving the pattern. After this user test about the intuitivity of the patterns we are able to allocate specific

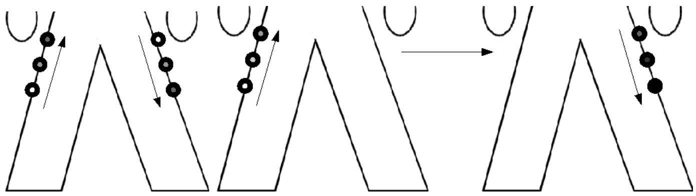


Figure 4.9: Simultaneous and compound rabbit patterns on the lateral side of the thighs

	Patterns for the upper body:		
1	$P^3(FMB_1)$	and	$P^3(BMB_1)$
3	$P^3(LLA)$	and	$P^3(LRA)$
4	$SP\_P(CB)$		
5	$SP\_P(FLA, BRA)$	and	$SP\_P(FRA, BLA)$
6	$R_U(FMB)$	and	$R_U(BMB)$
7	$R_U(LLB)$	and	$R_U(LRB)$
8	$R_L(FMB, LLB, BMB, LRB)$	and	$R_R(FMB, LRB, BMB, LLB)$
9	$(R_L(FMB, LLB, BMB, LRB))^2$	and	$(R_R(FMB, LRB, BMB, LLB))^2$
10	$R_L(FMB_{2+3}, LRB_{1+3}, BMB_{2+3}, LLB_{1+3})$	and	$R_R(FMB_{2+3}, LLB_{1+3}, BMB_{2+3}, LRB_{1+3})$
11	$SP\_R_U(FMB, LLB, LRB)$	and	$SP\_R_U(BMB, LLB, LRB)$
	Patterns for the legs:		
12	$SP\_R_D(FLT, FRT)$	and	$SP\_R_U(FLT, FRT)$
13	$SP\_R_D(BLT, BRT)$	and	$SP\_R_U(BLT, FRT)$
14	$SP\_R_D(FMT, BMT, LLT, LRT)$	and	$SP\_R_U(FMT, BMT, LLT, LRT)$
15	$SP\_R_{UD}(LLT, LRT)$	and	$SP\_R_{UD}(LRT, LLT)$
16	$CP\_R_{UD}(LLT, LRT)$	and	$CP\_R_{UD}(LRT, LLT)$

Table 4.3: Summary of the designed patterns

movement instructions to specific patterns. The next step is to test the patterns regarding their learnability and universality.

Before that, we will describe the design process of the garment to which the vibration motors are attached.

4.2.6 Garment Design

The employed vibration motors require the user to wear them directly against the skin or at least close to the skin.

Therefore a possibility to attach the motors in the required way on the body of the user has to be developed.

Hook-and-loop stripes

First we came up with the idea of hook-and-loop stripes, because they are easy to don and doff, adjustable to different girth and quite cheap. During user tests we detected that the inflexibility of the hook-and-loop stripes is a problem. When people tense or release their muscles the diameter of, for example, their arms changes and the fast-and-loop stripes slip or shift easily. Another problem we observed is that the fixed/solid material of the stripes propagates the vibration and the user can not locate a distinct point where the vibration occurs (diffuse vs isolated). Also it is important to mention that each stripe needs time to strap on and to position it accurately.

Tight fitting clothes

To overcome the problems of inflexibilty, slipping of vibration motors in position, and propagation of vibration we decided to use normal tight-fitting clothes (see figure 4.10). We have chosen waisted, long-sleeved shirts for women and a cycling short to ensure that the attached motors will have close contact to the skin. Because of the flexible material of the shirts and shorts they are appropriate for different girth. One drawback of this solution is that the shirts are not very tight at the back of the users resulting from the deepening by the spine. During the tests users stated that they have difficulties in perceiving the vibrations on the back. This circumstances is discussed in more detail in chapter 5.1—"Intuitiveness of the Designed Patterns" Results.
Another problem is still the long time it needs to attach the vibration motors. By attaching the actuators by snap fastener and sewing their wiring directly into the shirt, the process of putting on the tactor suit would be gradually simplified. This idea is already used by Arduino Lilypad [Buechley et al., 2008], but the vibration motor available is not sufficient for our application as the vibrations it causes are not strong enough.

Arduino Lilypad

Figure 4.10: Tight-fitting shirt and short with loops to add the vibration motors

Chapter 5

Evaluation of the Designed Patterns

"To acquire knowledge, one must study; but to acquire wisdom, one must observe."

— Marilyn vos Savant

The previously designed patterns (see table 4.3) are now evaluated in several user tests.

First of all it is examined if the designed patterns are intuitively associated to movements or body posture corrections. If they are, the tactile patterns are allocated to specific movement instructions, which have been chosen beforehand (see table 4.1).
When each movement instruction is assigned to a tactile pattern the learnability of this assignment is tested. It is of particular interest if these assignments are retrievable/available even in cognitive demanding tasks. Finally a user test in the field, while horse riding, is performed in which the perception and learnability of the tactile patterns for the different movement instructions are tested. This will inform us if the vibration frequency is sufficient when the subject is encountered environmental vibrations. Simultaneously it will reveal if the designed patterns are universal enough to be used for a real applications.

In the following user tests the participants wear the tight fitting shirt as well as the cycling short, which have been described in 4.2.6—"Garment Design", to attach the vibration motors on the user's body.
None of the participants have diseases, which can hamper the tactile perception. They do not get any gratification except candy.
In each user test the tactile movement instructions for the upper body and the legs are tested separately. Furthermore they are delivered in randomized order to avoid effects of learning.

Continuous improvements

During the evaluation of the designed patterns further modifications and redesigns of the patterns are done.

5.1 Intuitiveness of the Designed Patterns

Open Response Test

The designed patterns are first evaluated in an open response test. The tactile patterns are delivered to the subjects, which are subsequently asked to say what they intuitively would do or which body posture they would correct. The collected data will reveal if those patterns, which have been designed in 4.2.5—"Tactile Movement Instructions", can be inherently associated with a movement. Those patterns will require minimum training and the identification rate of those will not decrease considerably during physical activities. We define those patterns as being intuitive. During the test we are only interested in those movement which are deviated in chapter 4—"Designing the Tactile Feedback Patterns", see table 4.1 for comparison.

Intuitive pattern

5.1.1 Subjects

Nineteen computer science students and one translator participate in this user test. Twelve of them are males and eight females, which range in age from 22 to 28 years, with an average age of 25 years. Nineteen participants state that they regularly practice sports. None of the subjects report sensory difficulties.

Subjects do not have prior experience with tactile feedback except the mobile phone vibration alarm. Only one subject experienced tactile feedback in an evaluation of the Haptic Editor [Jonas, 2008].

5.1.2 Procedure

Participants are told that they will perceive tactile feedback at different body locations, which are intended to indicate body posture corrections. They are asked to say where they perceive the vibration and which association they have with the perceived vibrational signal. The patterns are repeated as often as the subject wants but mostly only once or twice. As participants rapidly cope with vibration stimuli and are able to express their impressions.
Participants are not aware of the nature of the rendered patterns or of the movements these patterns might represent.

Between group study

To figure out if one-element patterns are sufficient to indicate tactile movement instructions or if rabbit patterns are more suitable a between-group study is performed. This keeps the required time for the user test adequate, which takes about one hour. The subjects are evenly distributed over both groups. Group A gets one-element patterns for the upper body, whereas group B gets rabbit patterns. These two groups also differ in other patters that they get to keep the duration of the test as short as possible. In table 5.1 detailed overview is given, which patterns are transmitted to which group. The explanation of the body location abbreviations are given in table 4.2, whose location at the body is pictured in figure 4.2.

Nine patterns are given both groups because three of those patterns are the only possible patterns for this specific movement instruction (see table 5.1 (b)). These are simultaneous one-element patterns applied at the front of the shoulders or the arms.
The other six patterns are the third alternatives for similar patterns, which are already tested in group A and group B. In these patterns more than two body locations are used. Four of those patterns are simultaneous rabbit patterns delivered either to the torso or to the legs and two are rota-

(a)

Group A	Group B
One-element patterns:	Rabbit patterns:
$P^3(FMB_1)$	$R_U(FMB)$
$P^3(BMB_1)$	$R_U(BMB)$
$P^3(LLA)$	$R_U(LLB)$
$P^3(LRA)$	$R_U(LRB)$
Double rotational patterns:	Single rotational patterns
$(R_L(FMB, LLB, BMB, LRB))^2$	$R_L(FMB, LLB, BMB, LRB)$
$(R_R(FMB, LRB, BMB, LLB))^2$	$R_R(FMB, LRB, BMB, LLB)$
Simultaneous rabbit patterns:	Simultaneous rabbit patterns:
$SP\_R_D(FLT, FRT)$	$SP\_R_D(BLT, BRT)$
$SP\_R_U(FLT, FRT)$	$SP\_R_U(BLT, BRT)$
$CP\_R_{UD}(LLT, LRT)$	$SP\_R_{UD}(LLT, LRT)$
$CP\_R_{UD}(LRT, LLT)$	$SP\_R_{UD}(LRT, LLT)$

(b)

Patterns for both groups:
Simultaneous one-element patterns:
$SP\_P(CB)$
$SP\_P(FLA, BRA)$
$SP\_P(FRA, BLA)$
Simultaneous rabbit patterns:
$SP\_R_U(FMB, LLB, LRB)$
$SP\_R_U(BMB, LLB, LRB)$
$R_U(FLT, FRT, BLT, BRT, LLT, LRT)$
$SP\_R_D(FLT, FRT, BLT, BRT, LLT, LRT)$
Simultaneous rotational patterns:
$R_L(FMB_{2+3}, LLB_{1+3}, BMB_{2+3}, LRB_{1+3})$
$R_R(FMB_{2+3}, LLB_{1+3}, BMB_{2+3}, LRB_{1+3})$

Table 5.1: Tactile Patterns for the Intuitiveness Test

tional rabbit patterns. These rotational rabbit patterns draw two circles around the torso in contrast to the other tested rotational rabbit patterns which draw only one circle. For a detailed description of the patterns see chapter 4.2.5—“Tactile Movement Instructions”.

In group A we have to change the position of the motors once within the user test. The patterns which are given to group A for the upper body require 20 different body locations but only a limited number of vibration motors can be connected to a SensAct box. Three SensAct boxes are available that allow to connect 18 vibration motors. Therefore the pattern $SP\_P(CB)$ is delivered in the beginning or at the end of the sequence of patterns for not disturbing the user test procedure too often.

To eliminate any auditory cues from the vibration motors, subjects have to wear headphones. During the whole user test the subjects have to stand to guarantee equal conditions for all subjects.

5.1.3 Results

Participants are able to associate movement with tactile patterns. In doing so they prefer directional tactile cues (rabbit patterns) over one-element patterns, which vibrate only at one location. Responses user give to rabbit patterns are more concrete and more often associated to specific movements.

Rabbit patterns favored

Furthermore participants feel incited to move or correct the corresponding body location where the vibration occurs.

We will describe the results for each pattern type separately starting with the simple one-element patterns. One-element patterns are interpreted as upper body corrections when given to the back, chest or as simultaneous one-element pattern to the shoulders. In these cases users associate movements like leaning forward, leaning backward, and taking shoulders backward to the perceived patterns.
One-element patterns given to the lateral side of the arms are associated with lifting the corresponding arm but with none of the movement instructions we are interested in, like for example to lean the upper body to one direction. All movements to which we want to find tactile patterns are listed in table 4.1.
With simultaneous one-element patterns given to the front and back of the arms ($SP\_P(FLA, BRA)$ or $SP\_P(FRA, BLA)$) participants also associate movements of the arms. Few of the participants are incited to move the arms antiparallel and 50% of the participants do not know what movements they would perform.
Additionally participants need more time in processing si-

multaneous one-element patterns delivered to the arms as they occur at two different arms and two different locations.
Concerning one-element patterns some participants state that the vibration is not strong enough to motivate them to move.

Directional cues evoked by rabbit patterns yield more concrete answers. Rabbit patterns activated at the back or chest are associated with leaning forward, straighten up, or leaning backward. With $R_U(FMB)$ participants feel mostly incited to lean the upper body backward.
Similar results are gained when the rabbit pattern is applied to the lateral side of the upper body ($R_U(LLB)$, $R_U(LRB)$) or of the legs ($CP\_R_{UD}(LLT, LRT)$, $SP\_R_{UD}(LLT, LRT)$, $CP\_R_{UD}(LRT, LLT)$, $SP\_R_{UD}(LRT, LLT)$). Participants report to lean left or right, or to shift the weight to the left or right side. Half of the participants tend to move away from the vibration (c.f. "push"-metaphor) delivered to the upper body while the others are inclined to move towards the vibration (c.f. "pull"-metaphor). This proportion is not true for tactile patterns delivered to the legs. In this participants move away from the vibration.

Simultaneous patterns are processed slowly

Both the compound rabbit patterns and simultaneous rabbit patterns triggered at the lateral side of the thighs are associated to shift the weight to the opposite direction of a equivalent number of participants . Simultaneous patterns are processed more slowly than compound patterns as participants have to pay more attention in the directions of the two rabbit patterns presented simultaneously.

The results show that 60% of the participants intuitively associate to bend their legs when the pattern $SP\_R_D(BLT, BRT)$ is delivered, where three vibration motors on the back of each thigh vibrate successively top down. With the same tactile signal triggered at the front of the thighs fewer participants feel incited to bend their legs. Tactile directional cues in upward direction delivered to the thighs do not gain clear responses of the participants neither if they are delivered to the front or to the back of the thighs. Nevertheless some of the participants feel incited to stretch the whole body, the legs, or to jump.

Participants identify rotational patterns as a cue to turn the upper body. This is explicit in particular when the rotational pattern is given twice and fast around the torso ($(R_L(FMB, LLB, BMB, LRB))^2$, $(R_R(FMB, LRB, BMB, LLB)^2)$). In this pattern the standard stimulus duration (SD) is changed from 100msec to 50msec and a interstimulus duration (ISI) of 30msec. In this case the identification as a "turn-instruction" is twice as high as in the standard rotational pattern. In the standard rotational pattern the vibrations are perceived as localized taps instead of a continuous, directional movement.

Simultaneous patterns, which activate more than two rabbit patterns at the time (for example $SP\_R_U(FMB, LLB, LRB)$), and the rotational pattern, which triggers two vibration motors at the same time, evoke confusion by the participants. Less participants are able to associate a movement like before with a similar pattern. Furthermore they are described as being too strong and unpleasant. In the same way as simultaneous one-element patterns for the arms, these patterns effect longer processing times of the participants, which have difficulties in detecting the different body locations and directions.

Activating many motors simultaneously leads to confusion

5.1.4 Discussion

The results show that participants are able to associate body movements to tactile patterns. Based on the results we are able to observe trends in which way the designed tactile patterns can be used for tactile movement instructions or if a redesign is necessary to indicate the chosen movement instructions (see table 4.1)

Posture correction at vibration locus

One important thing is that vibrations are always associated with a correction of the corresponding body location where they occur. A vibration at a arm, for example, indicates that something has to be done with this arm.
Furthermore directional, rabbit patterns are preferred compared to one-element patterns as they indicate a direction for the movement instruction, while one-element patterns only indicate the part of the body where the correction of

the posture is needed.
Through the placement of the vibration motors participants are able to interpret the rotational pattern as cue to turn the upper body.

Not all obtained results are distinct. To assign specific movements to specific patterns we use the fact that countermovements are to be described (see table 4.1). The results show, for example, a clear tendency that leaning the upper body backward is associated to the rabbit pattern delivered to the chest ($R_U(FMB)$), therefore a rabbit pattern delivered to the back is used to indicate to lean the upper body forward ($R_U(BMB)$). If this is applicable further exploration have to show.
Although half of the participants will avoid the vibration ("push"-metaphor) and the other will not ("pull"-metaphor), we will use the "push"-metaphor in the following. These decisions help us to design a consistent set of tactile movement instructions.

No preferences are obtained if either compound or simultaneous rabbit patterns delivered at the lateral side of the thighs should be used to indicate a weight shift, this is decided with regard to the processing time. Participants take more time to perceive and recognize simultaneous rabbit patterns. Therefore compound rabbit patterns are assigned in the following with the movement instruction of shifting weight ($CP\_R_{UD}(LLT, LRT)$, $CP\_R_{UD}(LRT, LLT)$).

Simple patterns

The tactile patterns shall be kept simple to reduce the processing time a user needs to detect body location and direction. The results demonstrate that directional cues help to indicate what somebody has to do and in which direction. However activating too many vibration motors at the same time can counteract this benefit since this leads to confusions.

The resulting assignments of tactile patterns to movement instructions are listed below in table 5.2. For some of the movements it is not possible to allocate a pattern. For these movements new patterns will be designed, which are described in the next section.

As it is revealed in a previous user test (c.f. 4.2.1—

LF	$R_U(BMB)$
LB	$R_U(FMB)$
LL	new
LR	new
TSB	$SP\_P(CB)$
SLA	new
SRA	new
TL	$(R_L(FMB, LLB, BMB, LRB))^2$
TR	$(R_R(FMB, LRB, BMB, LLB))^2$
BL	$SP\_R_D(BLT, BRT)$
SL	$SP\_R_U(FLT, FRT)$
SWL	$CP\_R_{UD}(LRT, LLT)$
SWR	$CP\_R_{UD}(LLT, LRT)$

Table 5.2: Correlation of patterns and assigned movements

"Perception of Vibration on Different Parts of the Body") subjects are very sensitive to vibrations on the lateral side of the upper body. At this body location people are ticklish especially near the ala. Therefore the motor position at the lateral side (LLB and LRB) has to be changed or an alternative tactile pattern for leaning the upper body to one side has to be found.

Changing the vibration motor positions once within the user test for group A may have influenced the results for pattern $SP_P(CB)$ but further tests have to show.

The fact that the participants are standing during the whole test may have influenced the results. Although the compound patterns on the lateral side of the thigh evoke the movement to shift the weight to the left or right, it may not function in domains where the subject sits. Therefore we will also design alternative patterns for shifting the weight (SWL, SWR).

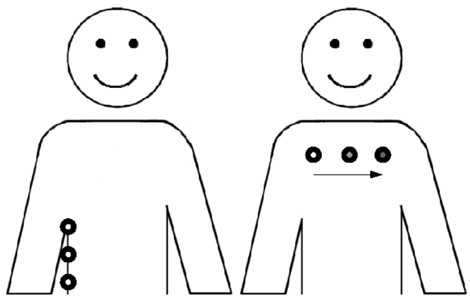
5.1.5 Improvements of the Tactile Design

In the previous user test it is obtained that subjects prefer directional cues given on the torso compared to one-element patterns. It has to be explored if this finding can be assigned to other body location or if these kinds of preferences are unequal for different body locations.

Therefore one-element patterns for swinging the arms antiparallel ($P^3(BRA)$ and $P^3(BLA)$) are explored. The vibration occurs either at the back of the right arm ($P^3(BRA)$) or at the back of the left arm ($P^3(BLA)$) to indicate that the arm has to be swung forward. This will speed up perception and recognition of the tactile movement instruction compared to the simultaneous one-element patterns $SP\_P(FLA, BRA)$ and $SP\_P(FRA, BLA)$. In the previous user test it is observed that the subjects take a long time to recognize where and what they perceived, when these patterns are triggered.
The vibration signal on the back of the arm shall push the corresponding arm forward without signaling to push the other arm backward. Because swinging the arms antiparallel is a natural movement it has to be explored if only one vibration signal will be sufficient.

Another movement instruction to which no pattern could be allocated is leaning the upper body to the right or left side. One idea is to dislocate the motors used in the rabbit pattern ($R_U(LLB)$, $R_U(LRB)$) 4,5cm lower (c.f. 4.2.1—"Vibration Motor Spacing") to bypass the sensitive area near the ala.
A second possible pattern is a simultaneous one-element pattern where all motors on the opposite lateral side vibrate at the same time to push the subject to the other side ($SP\_P(LLB)$, $SP\_P(LRB)$, see figure 5.1 (a)). This pattern uses the idea of pushing somebody with the hand in the desired direction. In the previous user test we only used single vibration motors to indicate this metaphor ($P^3(LLA)$, $P^3(LRA)$). Now we want to explore if a increase in vibration motor number gains better results.
A third possible pattern is a horizontal rabbit pattern that is delivered to the chest in left or right direction ($R_R(FCB)$, $R_L(FCB)$, see figure (5.1 b)). For this purpose we make use of two new motor positions that are 9cm to the left and right of the highest vibration motor position on the front of the upper body (FMB_1). This body location is named "front chest body" (FCB).

As mentioned in the discussion of the previous user test



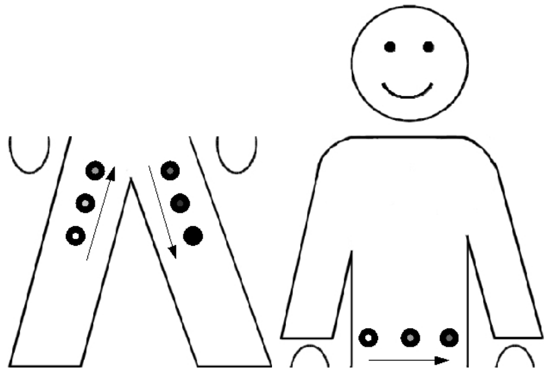
(a) all motors (b) left arrow

Figure 5.1: Two new possible patterns for leaning the upper body to the left

new patterns are also designed for the movement instruction of shifting the weight. Although subjects are able to associate shifting weight to the compound patterns delivered at the lateral side of the thighs ($CP\_R_{UD}(LLT, LRT)$, $CP\_R_{UD}(LRT, LLT)$), it is examined if other tactile patterns are useful. These may help to reduce the number of vibration motors used or to assure that the tactile pattern also works in other domains for example for those where the user sits.

We design three new patterns for shifting weight. The first is also a compound pattern but now delivered to the front of the thigh instead of the side. The two patterns for shifting the weight are $CP\_R_{UD}(FLT, FRT)$ and $CP\_R_{UD}(FRT, FLT)$, see figure 5.2 (a). In the second pattern a simultaneous one-element pattern ($SP\_P(LLT)$, $SP\_P(LRT)$) is used where all motors on the opposite side vibrate to push the user to the other side like for leaning the upper body to one side. In the third pattern the lower part of the upper body is used to give a horizontal rabbit pattern that describes an arrow to the left or right for indicating a weight shift ($R_R(FHB)$, $R_L(FHB)$, 5.2 (b)). The middle vibration motor is 4cm below FMB_1. The other two vibration motors are attached 9 cm to the left and right. This new body location is named "front hip body" (FHB).

Table 5.3 gives an overview of the newly designed patterns.



(a) front (b) left arrow

Figure 5.2: Two of the new possible patterns for shifting weight left

SLA:	$P^3(BLA)$
SRA:	$P^3(BRA)$
LL:	$R_U(LRB)$ $SP\_P(LRB)$ $R_L(FCB)$
LR:	$R_U(LLB)$ $SP\_P(LLB)$ $R_R(FCB)$
SWL:	$CP\_R_{UD}(FRT, FLT)$ $SP\_P(LRT)$ $R_L(FHB)$
SWR:	$CP\_R_{UD}(FLT, FRT)$ $SP\_P(LLT)$ $R_R(FHB)$

Table 5.3: Improvements in the Tactile Design (I)

5.1.6 Exploring the Improvements of the Tactile Design

In the previous user test 5.1—"Intuitiveness of the Designed Patterns" we discover that most of the designed patterns are intuitively understood by the subjects but there were a few movement instructions that could not be assigned to patterns. Therefore we designed new, alterna-

tive patterns for this movement instruction, see table 5.3 for comparison.
Now we will test if participants intuitively associate the corresponding movement instructions with the new designed patterns. The different alternatives for the same movement instruction are compared to the previous patterns, which rather would be assigned to those specific movement instructions. This explorations will lead to the possibility to assign patterns to those movement instructions to which were are not able to assign patterns yet (c.f. table 5.3).

As the patterns are designed in a complementary way for countermovements, only the patterns for swinging left arm forward and right arm backward (SLA), leaning upper body to the left (LL) and shifting weight to the left (SWL) are tested to reduce the time and effort of the user test.

Subjects

In this user test eleven computer science students participate to get a tendency if the new designed patterns are appropriate to indicate the corresponding movement instructions. In the user test five female and six male subjects take part. Subjects range in age from 20 to 27 years, with an average age of 24 years. All except one participants practice sport regularly. None of the subjects reported any sensory difficulties.

To have the same premises like in the previous user test we choose subjects that do not have any experience with tactile feedback before except with mobile phone vibration alarm.

Procedure

The experimental procedure is similar to that of the previous user test. To be able to compare the new with the old patterns, participants get the new as well as the old patterns for a corresponding movement instruction.
During the test procedure the eight different patterns are

given randomized across the subjects but patterns for the same movement instruction are given successively. The eight different patterns are listed in table 5.4.

SLA:	$P^3(BLA)$
	$R_U(LRB)$
LL:	$SP\_P(LRB)$
	$R_L(FCB)$
	$CP\_R_{UD}(FRT, FLT)$
SWL:	$SP\_P(LRT)$
	$R_L(FHB)$

Table 5.4: Patterns to verify the improvements

After each delivered pattern subjects are asked where they perceive the vibration, if there is a specific direction, and if they can associate any movement or body posture correction with the given pattern. Participants are not aware of the nature of the rendered patterns or of the movements these patterns might represent. After each pattern for the same movement instruction is delivered to the subjects, they are told which movement instruction these patterns might represent. Subsequently subjects are asked which of the presented patterns they prefer for this movement instruction or if they have other ideas to signal this movement instruction.

During the test the subjects have to stand upright for providing the same conditions for each subjects. Additionally they have to wear headphones to eliminate any auditory cues from the motors.

Results

The results show that 54% of the subjects associate leaning to the left with pattern the rabbit pattern triggered at the lateral right sight of the upper body $R_U(LRB)$, 22% with a horizontal rabbit pattern delivered to the chest $R_L(FCB)$ and 9 % with a simultaneous one-element pattern $P^3(LRB)$, see figure 5.3 for comparison. 45% of the

subjects prefer pattern $R_U(LRB)$, 27% pattern $R_L(FCB)$, and 18% pattern $P^3(LRB)$, see figure 5.3 for comparison. One of the subjects does not prefer any of these patterns.
It is important to mention that more subjects associate to turn the upper body to the left with pattern $R_L(FCB)$ (36%) than with leaning the upper body to the left (only 22%). With $P^3(LLB)$ more subjects associate leaning the upper body to the right (36%) than with leaning it to the left.

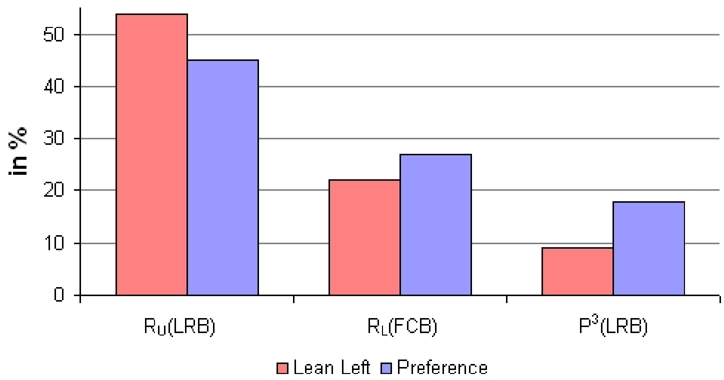


Figure 5.3: Associations and preferences given by the participants concerning "lean left" instruction

The pattern for the movement instruction swinging the left arm forward and the right arm backward derives not the desired results. Again the subjects have problems with perceiving and localizing the vibrations on the upper arm. 18% of the subjects associate swinging the left arm forward and the right arm backward with pattern $SP\_P(FRA, BLA)$ and 27% of the subjects associate swinging only the left arm forward with pattern $P^3(BLA)$. The subjects realize that they have something to do with their arm but do not understand the meaning of the pattern.
36% of the subjects prefer pattern $SP\_P(FRA, BLA)$ and 9% prefer pattern $P^3(BLA)$. The other subjects neither prefer a pattern.

The results for shifting the weight to the left show, that giving the vibration signals on the lateral side ($CP\_R_{UD}(LRT, LLT)$) of the thigh is associated with shift-

ing weight. 63% of the subjects intuitively shift their weight to the left, see figure 5.4 for comparison. All subjects (91% of the subjects) except one prefer this pattern over rabbit patterns delivered at the front or simultaneous one-elemenet patterns at the lateral side of the thigh.
The same pattern given on the front of the thigh, pattern $CP\_R_{UD}(FRT, FLT)$, works also very well but only 50 % of the subjects associate shifting weight to the left with this pattern. 27% of the subjects associate to shift weight left with pattern $SP\_P(LRT)$ and no subject with pattern $R_L(FHB)$.
With pattern the horizontal rabbit pattern $R_L(FHB)$, similar to pattern $R_L(FCB)$, subjects (45%) associate turning the upper body to the left. Furthermore this body location, FHB, is described as being ticklish.
Subjects state that for indicating shifting the weight to the left the upwards movement of the vibration will be sufficient.

Figure 5.4: Associations and preferences given by the participants concerning "shift weight left" instruction

During the user test we ask the subjects if they would sidestep the vibration or not. 50% of the subjects would sidestep and 50% would not sidestep.

Discussion

The results suggest that rabbit patterns are superior to one-element and simultaneous one-element patterns even at different body locations. Driven by that it is decided to use the idea of directional cues for all movement instructions, except taking shoulders backward. The simultaneous one-element pattern for this specific movement instructions ($P^3(CB)$) is an exception of this finding as the results do not require the use of rabbit pattern.

Use rabbit patterns

The results show that the previous designed pattern $R_U(LRB)$ was the right idea but on the wrong body location. With disarranging the motor position further down subjects are able to perceive the signal without being tickled and to associate the movement instruction leaning left. With the horizontal rabbit pattern $R_L(FCB)$ more subjects associate turning the upper body. This conclusion can be used in further developments of a tactile language.

The pattern for pushing the left arm forward and right arm backward is especially hard to recognize for the subjects. On the one hand the single vibration is hard to perceive and recognize, on the other hand it seems to be very difficult to localize the vibration being at the front or at the back of the arm. A given direction in the vibrational signal will provide the user more time to perceive, recognize, and localize the vibration.

Shifting the weight to the left confirms that pattern $CP\_R_{UD}(LRT, LLT)$ is intuitively understood by the user. The new designed patterns does not provide any improvements in the pattern recognition. If there is only a limited number of vibration motors available, the results reveal that it is also possible to use the pattern $CP\_R_{UD}(FRT, FLT)$ as 50% of the subjects intuitively associated to shift the weight left.
Because the subjects are standing throughout the whole user test we are not able to state if the designed patterns also work when the subjects are sitting and which of these patterns will be preferred in this case.

In the following it has to be investigated if it is sufficient to give the user only an upwards rabbit pattern on the lateral side of the right thigh to indicate shifting the weight to the left in contrast to simultaneous or compound rabbit patterns. If it is sufficient the vibration signal is shortened, which will be desirable in fast sports.

The results allow us to assign a tactile pattern to each movement instruction we are interested in. The table 5.5 shows all actual assignments.
As we have not found a new pattern for the movement instruction to swing the arms antiparallel, we assign the simultaneous one-element pattern to this. The test about the learnability will show in which way the slow processing times of these patterns will influence the identification performance.
To the movement instruction of shifting weight to alternative patterns are assigned, which will be compared in the following user test.

LF	$R_U(BMB)$
LB	$R_U(FMB)$
LL	$R_U(LRB)$
LR	$R_U(LLB)$
TSB	$SP\_P(CB)$
SLA	$SP\_P(FLA, BRA)$
SRA	$SP\_P(BRA, FLA)$
TL	$(R_L(FMB, LLB, BMB, LRB))^2$
TR	$(R_R(FMB, LRB, BMB, LLB))^2$
BL	$SP\_R_D(BLT, BRT)$
SL	$SP\_R_U(FLT, FRT)$
SWL	A: $CP\_R_{UD}(LRT, LLT)$ B: $R_U(LRT)$
SWR	A: $CP\_R_{UD}(LLT, LRT)$ B: $R_U(LLT)$

Table 5.5: Assignment of patterns to movements concerning the intuitiveness

The aspect that half of the subjects would sidestep from the vibration and half of the subjects would not, requires further analysis. It has to be determined if subjects can learn to do the opposite thing that they would intuitively do or if the resulting language has to be adopted to the preferences of the user.

5.2 Learnability of the Designed Patterns

After we have explored the intuitiveness of the designed patterns it has to be explored if participants are able to learn these patterns and their assigned movement instructions (see table 5.5). The tactile patterns shall be used to give users continuous feedback about their current body posture, therefore it is necessary that users are able to easily transfer the meaning of the different patterns to correct their body posture.

Since the designed tactile movement instructions shall also be suitable for real applications, they have to be tested in cognitive demanding tasks, which can degrade the performance in identifying tactile patterns [Bhargava et al., 2005].

To assure that the learned patterns can be easily memorized and recognized we perform two tests one in a relaxed and one in a cognitive load condition. These two tests will shed light on the intuitiveness, learnability, and differentiability of the designed patterns. Furthermore we test the subjects on the following day to determine if they can remember the tactile patterns over a fixed period of time (one day).

5.2.1 Subjects

In this user test 17 subjects, 4 female and 13 male, participate. They range in age from 19 to 30 years, with an average age of 25 years. Of the seventeen participants fifteen are computer science students and two are pupils. Three of the subjects do not practice any sports. None of the subjects report any sensory difficulties.

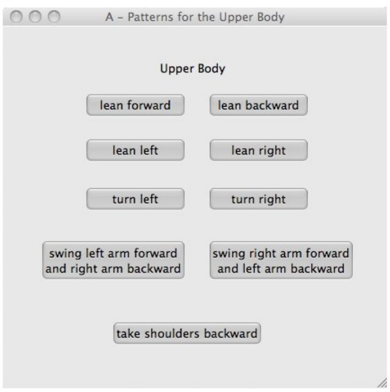
In contrast to the previous user tests eight of the subjects participated in preceding user tests and therefore have experience with tactile feedback.

5.2.2 Procedure

This user test is divided into a training phase, test phase and retention test. In the training phase participants train the allocation of patterns to specific movement instructions. In the test phase it is tested if they have memorized the patterns of the different movement instructions. At the second day in the retention the same procedure as on the previous day is adhered but without a training phase beforehand. In the following the procedure of training phase and test phase is described.

Training Phase

Due to the fact that the learnability of the designed patterns is tested, each subject is given time to learn the patterns, which are associated to movement instructions. The training time lasts at most ten minutes but none of the subjects make use of this time.
Patterns for the upper body and for the legs are learned and tested separately because of the limited number of hardware. The used GUI for the training phase is shown in figure 5.5. Each subject activates the patterns by pressing dedicated buttons on a GUI. The buttons are labeled with the appropriate instructions, such as “bend knees” or “turn left”. Depending on whether the subjects have to learn the patterns for the upper body or the legs, the left or right window is shown.



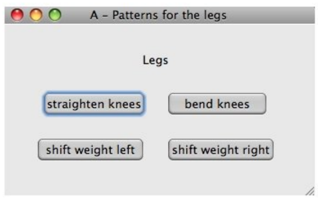


Figure 5.5: Screenshot of the implemented GUI for learning the tactile Patterns

A between group test is performed to limit the time of the user test for each participant to about one hour, including donning/doffing and debriefing. The patterns are distributed across both groups.

Between-group test

Group A and B get the same patterns except for shifting the weight to the left or to the right. As described in user test 5.1—"Intuitiveness of the Designed Patterns", it is found out that subjects detect the pattern shifting weight left or right before the vibration ends. Group A gets the compound patterns (SWL_A and SWR_A) while group B gets the rabbit patterns (SWL_B and SWR_B).

Table 5.5 gives an overview of all patterns that are tested during this user test.

Testphase with relaxed condition

After the training phase two different tests are carried out. In the first test, relaxed condition, the subjects have to wear headphones to eliminate auditory cues from the vibration motors. The different patterns are presented in randomized order either for the upper body or the legs. Each pattern is presented two times. After each presented pattern the subject is asked to state which of the patterns is delivered. The randomization of the pattern order is necessary to reduce the influence of learning effects.

Testphase with cognitive load condition

In the cognitive load condition subjects have to play a Balance Game , Snowboard Slalom, on the Nintendo Wii Fit[1] , while simultaneously perceiving tactile movement instructions and giving feedback about which pattern they perceive. In figure 5.6 the setup of the cognitive load condition is shown. We are interested in the recognition performance of the different patterns while subjects are doing a cognitive demanding task. Subjects get the possibility to learn how to balance on the Wii Fit Board for two snowboard-runs before the identification test with cognitive load starts.

During the whole user test subjects have to stand to guarantee the same conditions during the relaxed and the cognitive load condition. If the subjects continuously confound patterns during the first day, we inform them after the last test of the first day.

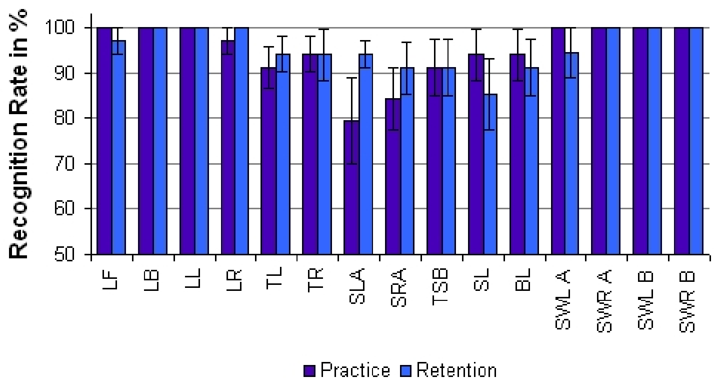
[1] http://www.nintendo.com/wiifit/launch/?ref=

Figure 5.6: Setup of the cognitive load condition of the experiment

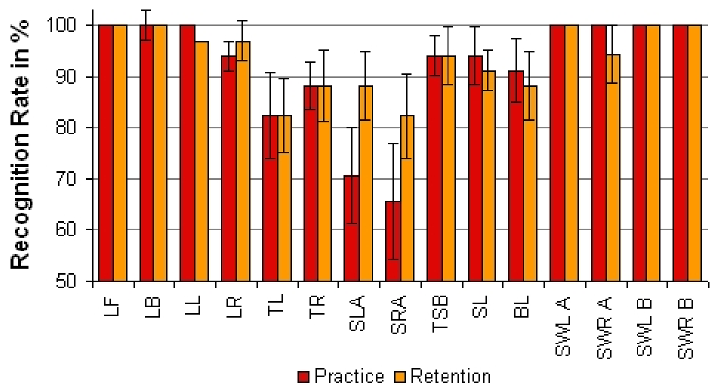
5.2.3 Results

Overall no problems arise for learning and remembering the tactile patterns associated to movement instructions over a fixed period of time.
The resulting correct identifications of the different patterns in the relaxed condition and in the cognitive load condition are illustrated in figure 5.7. The diagrams show how good each pattern is recognized in the practice test at the first day and in the retention test at the second day. All obtained results are above chance level, which is 25% for patterns of the legs and 11% for patterns of the upper body. The recognition rates perceived in the retention test are mostly equal or better than in the practice test.

The results show that the recognition rate for some patterns degrades under cognitive load. This is also revealed by the average identification of all patterns in the relaxed condition, which is 95% whereas in the cognitive demanding task it is 93%. This yields in an average overall identification rate of 94%.
The diagram of the identification rate for each pattern in re-



(a) relaxed



(b) cognitive

Figure 5.7: Recognition rate of the tactile patterns in relaxed and cognitive load condition (with standard error)

laxed and in the cognitive load condition averaged over the practice and retention test is shown in figure 5.8.

In the following we will point out the significant variations in the identification rate for the different tactile patterns. As mentioned before some of the designed tactile patterns are identified really good with a recognition rate of 100% or at least 97% (see figures 5.7, 5.8). These patterns are leaning the upper body in any direction (LF,LB, LL, LR) or shifting the weight to the left or right (SWL or SWR) for both groups.

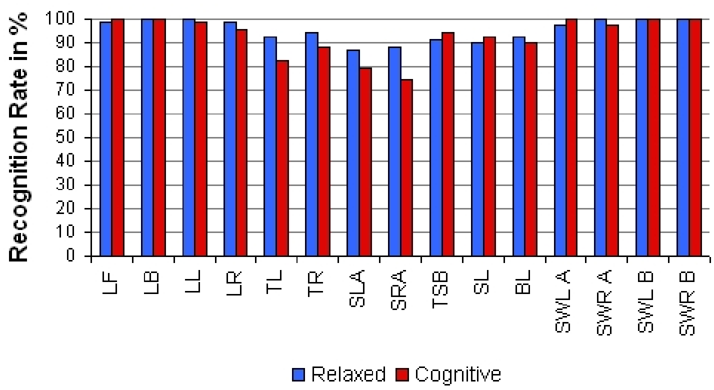


Figure 5.8: Averaged recognition rate of the tactile patterns in relaxed and cognitive demanding condition (with standard error)

The recognition rates for the other patterns are worse. The movement instruction of taking shoulders backward (TSB) has similar recognition rates in relaxed and cognitive load condition, which are above 90%. The results during the cognitive load condition are even better.
These results are similar to those for bending legs (BL) and stretching legs (SL), which have a overall recognition rate of around 90% but the deviations between the two condition and concerning the retention test are larger.

In the relaxed condition the identification rate of the other tactile patterns is between 79% and 94% but with cognitive load the recognition rate degrades significantly. These patterns are for the movement instructions of turning left or right (TL, TR) and swinging arms antiparallel (SLA, SRA). The overall identification rate for TL and TR are around 90%, namely 88% for TL and 91% for TR, while it is 81% for pattern SRA and 82% for SLA.
The worse recognition rates for turning the upper body are due to the fact that participants confound the direction of the indicated turn.
The recognition rate for pattern swinging left arm forward and right arm backward (SLA) degrades under cognitive load about 10%. For SRA the decrease is even larger with a deviation of 20 %. Participants confounded these two patterns but also forget the association.

5.2.4 Discussion

This user test shows that most designed patterns work in an intuitive or at least learnable way, whereas the cognitive load condition reveals that movement instruction need further investigations. Those patterns whose recognition rate degrades significantly under cognitive load appear to be less learnable.

Overall identification rate of 94%

The received average overall identification rate is 94%, whereas the average identification rate in relaxed condition is 95%, which is similar to the results of Chan et al. [2005]. In their work the users' ability to identify 7 haptic stimuli and their haptic labels is evaluated. In the absence of workload each stimuli is typically identified with 95% accuracy.

Patterns for leaning the upper body in any direction (LF, LB, LL, LR) and shifting the weight (SWL, SWR) are identified with nearly 100% accuracy. The results show that both pattern types for shifting the weight to the left or to the right (SWL_A, SWL_B, SWR_A, SWR_B) are identified in the same way with those of group B a little bit better. Based on this results we will use in the following the simple rabbit patterns SWL_B and SWR_B instead of those patterns for group A, which are compound rabbit patterns, because they are shorter. Delivering movement instructions with short tactile patterns will be desirable in fast sports.

The patterns for straightening or bending the legs (SL, BL) as well as taking shoulders backward (TSB) do not have such a good identification rate as those previously described patterns but their identification rate is around 90%, which is acceptable.
Nevertheless further analysis are carried out to determine if subjects confound the meaning of the patterns for bending and straightening knees or if they have difficulties in perceiving the vibrational signal.

The cumbersome patterns are for the movement instructions to turn the upper body (TL, TR) or to swing the arms antiparallel (SLA, SRA). Although the users judged the tactile patterns for turning the upper body as very intuitive (5.1—"Intuitiveness of the Designed Patterns"), some problems arise during the user test. Subjects are not able to differentiate these two directions especially under cognitive load. Therefore we decide to modify or redesign the turn-patterns to improve the identification accuracy.

The problems with swinging the arms antiparallel are first identified in a previous user test (c.f. 5.1.5—"Improvements of the Tactile Design"). Now we have gained the confirmation in which way the simultaneous one-element patterns delivered to the arms degrade the perception and recognition of the pattern.
Due to the fact that we do not have enough SensAct boxes available we were not able to test alternatives to the patterns SLA and SRA at the same time. This requires switching the vibration motors to different body locations. The results of this user test demonstrate that a redesign of the tactile patterns for swinging the arms is particularly required.

Table 5.6 shows the status quo of the assignments of tactile patterns to movement instructions. As it is indicated in the table four patterns have to be redesigned to improve the recognition rates.

LF	$R_U(BMB)$
LB	$R_U(FMB)$
LL	$R_U(LRB)$
LR	$R_U(LLB)$
TSB	$SP\_P(CB)$
SLA	new
SRA	new
TL	new
TR	new
BL	$SP\_R_D(BLT, BRT)$
SL	$SP\_R_U(FLT, FRT)$
SWL	$R_U(LRT)$
SWR	$R_U(LLT)$

Table 5.6: Assignment of patterns to movements concerning the learnability

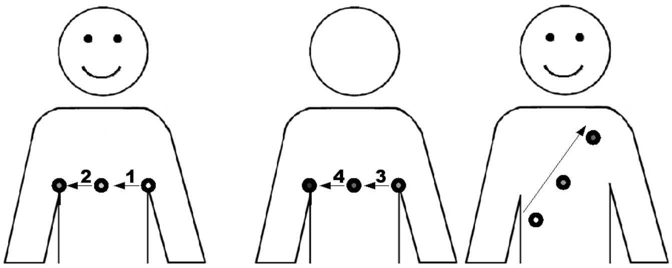
5.2.5 Improvements of the Tactile Design

In the user test about the learnability of the association of tactile patterns to movement instructions we find out that the most patterns work in the desired way but the patterns for turning the upper body and swinging the arms need a redesign. The figures 5.9 and 5.10 give a visualization of the idea of the new designed patterns.

The subjects stated that they find it intuitive to detect that TL and TR indicate to turn the upper body to the left or to the right. The identification tests under cognitive load demonstrate that people are not able to recognize in which direction they have to turn. Therefore a new pattern is designed where the direction in which the user has to turn is obvious.

The first new designed pattern for the turn-instruction is similar to the previously used pattern but with two distinct starting points. The pattern for turning the upper body to the left starts at the right side of the body and proceeds left around the torso (TL_A = $(R_L(LRB, FMB, LLB, BMB))^2$, see 5.9 a) while the pattern for turning the upper body to the right is designed in an analogous way (TR_A = $(R_L(LLB, BMB, LRB, FMB))^2$). It has to be discovered if the recognition rate of the turn pattern is improved by two distinct starting points.
The second possible pattern for turning the upper body is a rabbit pattern that "draws" a diagonal line at the front of the upper body. For turning the upper body to the left the vibration starts at the bottom right and ends at the top left of the upper body (TL_B = $R_{dia}(FWB_1, FMB_2, FCB_3)$), see figure 5.9 b. For turning the upper body to the right the pattern TR_B = $R_{dia}(FWB_3, FMB_2, FCB_1)$ is designed analogous. This pattern used the previously introduced body location FCB (front chest body) and a new body location "front waist body" (FWB). The middle vibration motor of FWB is FMB_1. The other two vibration motors are attached 9 cm to the left and right.

The redesign of the patterns for swinging the arms (SLA, SRA) was first recommended in chapter 5.1—"Intuitiveness of the Designed Patterns". To improve the



(a) distinct starts (b) diagonal

Figure 5.9: New Patterns for turning the upper body to the left

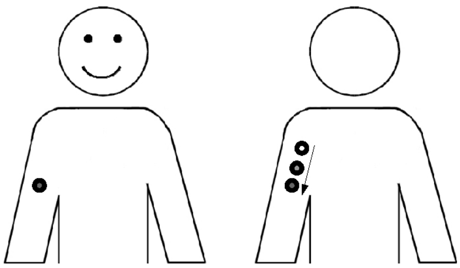


Figure 5.10: New rabbit pattern for swinging the left arm forward and the right arm backward

pattern recognition a rabbit pattern at the back of the upper arm in combination with a one-element pattern at the front of the other arm is used to indicate the direction in which the user has to swing his arms (SLA_n = $R_D(BRA)$ + $P^3(FLA)$ and SRA_n = $R_D(BLA)$ + $P^3(FRA)$, see figure 5.10).

In the design no simultaneous rabbit pattern is used as further results suggest that this would lengthen the perception time like it was the case for the pattern for shifting weight (c.f. $SP\_R_{UD}(LLT, LRT)$).

Table 5.7 gives an overview of the new designed patterns for the two different movement instructions.

TL:	$(R_L(LRB, FMB, LLB, BMB))^2$ $R_{dia}(FRBB, FMB_2, FCB_3)$
TR:	$(R_L(LLB, FMB, LRB, BMB))^2$ $R_{dia}(FLBB, FMB_2, FCB_1)$
SLA:	$R_D(BRA)$ + $P^3(FLA)$
SRA:	$R_D(BLA)$ + $P^3(FRA)$

Table 5.7: Improvements of the Tactile Design (II)

5.2.6 Exploring the Improvements of the Tactile Design

In this user test it is examined if the modifications of the tactile design are beneficial over the previously used patterns. Again we will test if participants are able to learn the new designed patterns and their assigned movement instructions (see table 5.7).

Additionally we will test the perception of directional cues delivered at the thighs. Through this we want to explore if the worse recognition rates for bending and stretching legs are due to a bad perception or due to the fact that participants confound the two patterns.

Subjects

Twenty subjects participate in this user test with an age between 21 and 53 years, with an average age of 28 years. Eight of the participants are female and twelve male. Ten students and ten none students participate. Five of the participants do not practice sports regularly. None of the subjects report any sensory difficulties.

To have the same premises as in the previous user test non of the subjects took part in the previous user test about the learnability of tactile patterns. Two of the subjects participated in user tests about the intuitivity of tactile patterns.

Procedure

The user test has the same structure and procedure as the previous user test, except the case that no retention test is performed.
In this test the chance is caught to test further modifications of the functioning patterns for leaning the upper body in any direction. With this it is explored if instead of letting each motor vibrate three times a single vibration or another order of vibrations is also able to transmit a directional cue and achieves similar recognition rates as the originally used rabbit patterns.
In the first group of patterns for leaning the upper body in any direction each of the three vibration motors only vibrates once. This type of pattern is in the following called single rabbit pattern (R^1). For example is $R^1_U(BMB) = P^1(BMB_3) \rightarrow P^1(BMB_2) \rightarrow P^1(BMB_1)$ the pattern for the movement instruction leaning forward.

Single rabbit pattern

For the second group of patterns for leaning the upper body in any direction an idea is taken from Geldard [1975] for sensory saltation. In this group there are again three single vibration stimuli but only on two distinct sites. The first two vibrations are delivered at the first motor of the body location, while the third is delivered at the third vibration motor of the body location ($R^G_U(BMB) = P^1(BMB_3) \rightarrow P^1(BMB_3) \rightarrow P^1(BMB_1)$. This type of pattern is called "Geldard" rabbit pattern.

"Geldard" rabbit pattern

To test all this patterns we divided the subjects into two groups. Group A gets the single rabbit patterns and the new rotational rabbit pattern, whereas group B gets the Geldard rabbit pattern and the diagonal turn pattern. Both groups get the new pattern for swinging the arms. The pattern for taking shoulders backward is also given to have the same number of patterns that are to be learned in the training phase like in the previous test about the learnability. In table 5.8 the distribution of the patterns over both groups is shown.

Between-group test

All this patterns are tested, after a short training phase, in the relaxed and cognitive demanding condition.

After the patterns for the upper body have been tested, the perception of different directional cues given on the thighs

Instruction	Group A	Group B
	Single rabbit patterns:	"Geldard" rabbit patterns:
LF	$R_U^1(BMB)$	$R_U^G(BMB)$
LB	$R_U^1(FMB)$	$R_U^G(FMB)$
LL	$R_U^1(LRB)$	$R_U^G(LRB)$
LR	$R_U^1(LLB)$	$R_U^G(LLB)$
	Double rotational patterns:	Diagonal rabbit pattern:
TL	$(R_L(LRB, FMB, LLB, BMB))^2$	$R_{dia}(FRBB, FMB_2, FLTB)$
TR	$(R_R(LLB, FMB, LRB, BMB))^2$	$R_{dia}(FLBB, FMB_2, FRTB)$
	Both Groups	
SLA	$R_D(BRA) + P^3(FLA)$	
SRA	$R_D(BLA) + P^3(FRA)$	
TSB	$SP\_P(CB)$	

Table 5.8: Tactile patterns for the learnability test

are tested under cognitive load.
In a randomized order the subjects get the following directional cues: upwards rabbit pattern on the front of the thighs ($FU = SP\_R_U(FLT, FRT)$), upwards rabbit pattern on the back of the thighs ($BU = SP\_R_U(BLT, BRT)$), upwards rabbit pattern on the front and back of the thigh ($FBU = SP\_R_U(FLT, FRT, BLT, BRT)$), as well as a downwards rabbit pattern on the front ($FD = SP\_R_D(FLT, FRT)$), back ($BD = SP\_R_D(BLT, BRT)$), and on the front and back of the thighs ($FBD = SP\_R_D(FLT, FRT, BLT, BRT)$).

Results

Each pattern is tested by at least ten subjects. The patterns for swinging the arms (SLA, SRA) have been tested by nineteen subjects as they are tested in both groups. One participant wears instead of the long-sleeved tight fitting shirt, shown in figure 4.10, a short-sleeved tight fitting shirt because of his upper arm diameter.

In the following figures the results for the different patterns for group A and B are shown in comparison to the results that are gained in the previous learnability test. While a retention test is not accomplished in this user test, the results are compared to those of the first day.

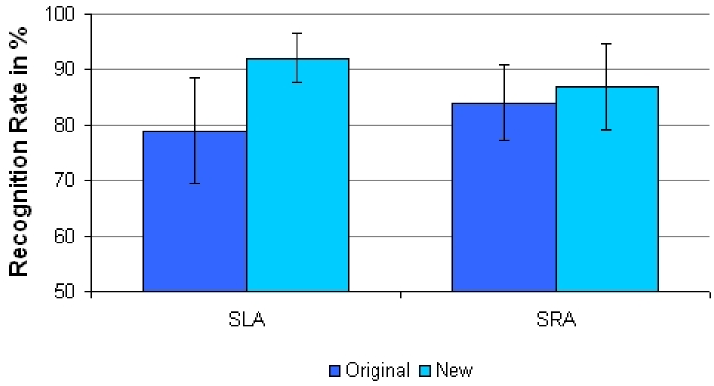
The results for swinging the left arm forward and the right arm backward or the other way around significantly show, that the redesign of the pattern is an essential improvement, as is pictured in figure 5.11. While the identification rates for the previously used patterns is between 66 % and 84 %, the identification rate for the new designed patterns is between 87 % and 95 % in relaxed and cognitive demanding condition. This shows that directional cues are again beneficial over single vibration stimuli. The overall recognition rate of the tactile pattern for this movement instruction is 91%.

Rabbit pattern benefical over simultaneous one-element pattern

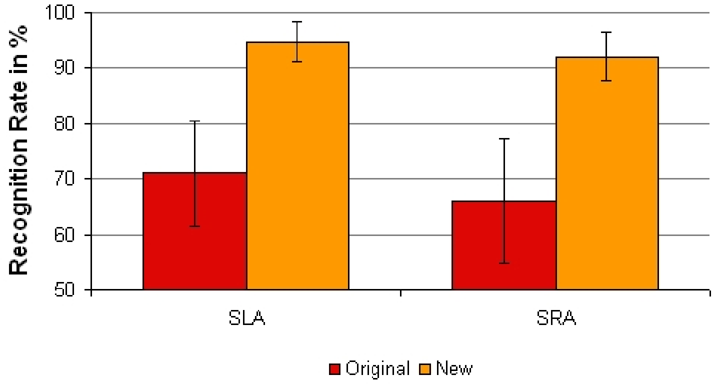
The new pattern designs for the movement instruction turning the upper body to the left or to the right does not bring the desired improvements, see figure 5.12. Although the recognition rate in the relaxed condition is improved with the new patterns compared to the previous pattern, the results in the cognitive demanding condition vary. For turning left their is still an improvement compared to the previous pattern but for turning right the recognition rate significantly degrades. In group A the participants confound the pattern TR with pattern TL, while in group B the answers vary between LB, TSB, or SRA.

In figure 5.13 the results of the different lean patterns are shown. Except for leaning right (LR) in the cognitive load condition the recognition rate for the normal rabbit patterns are better than the new designed rabbit patterns. For LF and LB the recognition rate for the normal rabbit pattern and this of group A, single rabbit pattern, are identical at least in the relaxed condition. The recognition rates for the patterns of single group A (single rabbit pattern) are better than those of group B (“Geldard” rabbit pattern).

In figure 5.14 the perception rates of different directional cues given on the thighs are shown. The results reveal that participants are nearly always able to perceive the direction and location of the vibrational cue. They have more difficulties in perceiving the locus of vibration when the front and the back of the thighs are stimulated simultaneously.



(a) relaxed



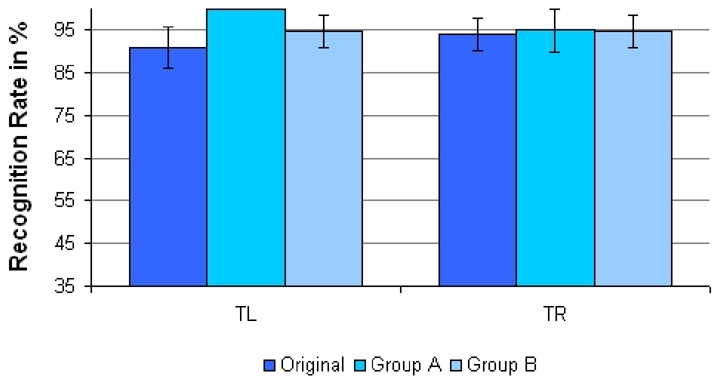
(b) cognitive

Figure 5.11: Recognition rate of the tactile patterns for swinging the left or right arm forward (with standard error)

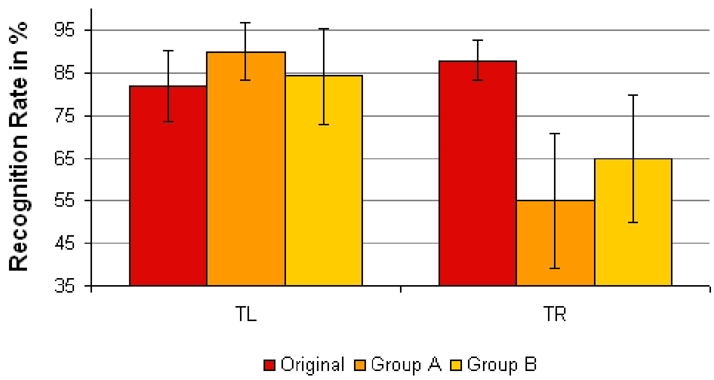
The accuracy of rabbit patterns triggered in downwards direction at the back of the thighs is with 100% the best, followed by downwards direction and upwards direction at the front of the thighs.

Discussion

This experiment shows that the redesign of the patterns for the movement instruction for swinging the arms are bene-



(a) relaxed

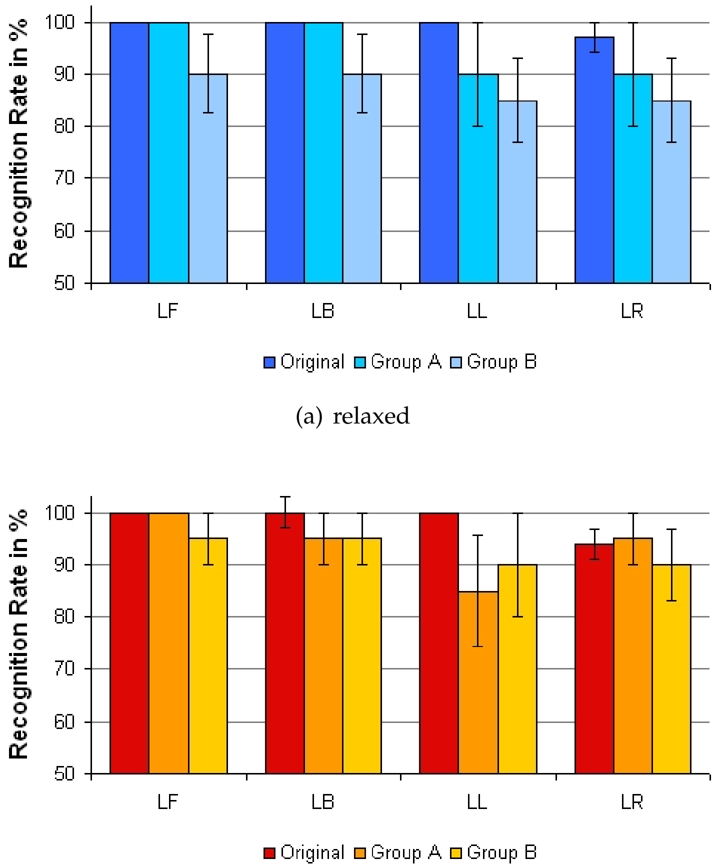


(b) cognitive

Figure 5.12: Identification rate of the tactile patterns for turning the upper body to the left or right (with standard error)

ficial but other patterns need further redesigns. Using directional cues at the back of the upper arm achieve better recognition rates as the previously used simultaneous one-element patterns. Therefore we replace the previously used patterns $SP\_P^3(FRA, BLA)$ and $SP\_P^3(FLA, BRA)$ with the rabbit patterns $R_D(BLA) + P^3(FRA)$ and $R_D(BRA) + P^3(FLA)$.

Redesigning the turn-pattern does not effect the desired improvements of the recognition rate. The turn-pattern with different starting points (group A), achieves higher recog-



(a) relaxed

(b) cognitive

Figure 5.13: Identification rate of the tactile patterns for leaning the upper body in any direction (with standard error)

nition rates in the relaxed condition but in the cognitive demanding condition only for turning left. For turning right the recognition rate degrades dramatically. In these cases the participants recognize the TR pattern as a TL pattern. This suggests that the different starting points are not sufficient to indicate a left or right turn.
The diagonal rabbit pattern (group B) for indicating a turn is not superior over the other turn-patterns.
Participants confound the diagonal turn-pattern with LB, TSB, or SRA. This shows that the participants not always identified the diagonal pattern as a turn pattern but con-

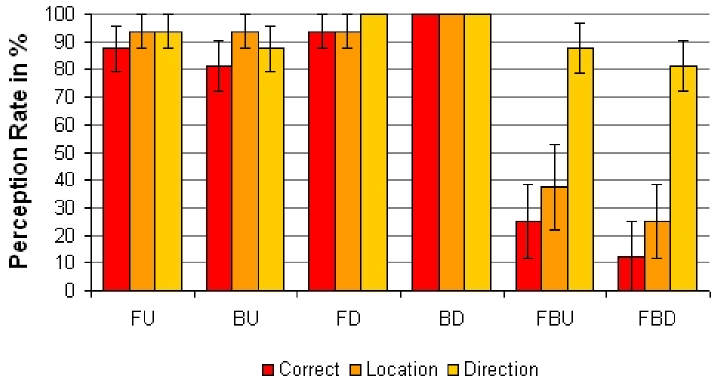


Figure 5.14: Perception rate for directional cues delivered at the thighs (with standard error)

found this pattern with similar patterns. This finding is consistent with those of Geldard and Sherrick [1965], who states that participants more likely confound patterns that share the same vibration motors. The results reveal that the diagonal turn-pattern is not appropriate and will be discarded.
Therefore the pattern for the movement instruction "turn the upper body" still requires more investigations especially concerning the confounding of left and right. It is possible that the higher average age and the higher number of non-students influenced the results in that way that these people take more time to internalize the meaning of the patterns.
In further investigations the horizontal rabbit patterns, $R_L(FCB)$ and $R_L(FCB)$, should be explored.

The recognition rates for the variations of the different lean patterns (LF, LB, LL, LR) show that the originally used rabbit pattern is superior over the new designed lean-patterns. The single rabbit pattern is rather comparable to the original rabbit pattern than the "Geldard" rabbit pattern. If a shortening of the tactile movement instruction is required the single rabbit pattern can be used but does gain the worse recognition rates.
The findings suggest that the originally used rabbit pattern is, in contrast to the new designed rabbit patterns, long enough to be detected.

The investigation concerning the perception of directional cues at the thighs shows that the perception of directional cues as long as given at the front or at the back of the thighs is quite good. The perception rate in these cases varies between 81% and 100%. Problems arise when the vibration stimulus is given simultaneously at the front and back of the thighs. The perception rate in these cases degrades significantly (25% and 13%).
This indicates that the recognition rates in the previous learnability test for straightening (94%) and bending the legs (91%) can partly be ascribed to a bad perception and partly to the confounding of the meaning of the two patterns. The perception of the BL pattern is 100% but nevertheless the recognition rate in the previous test is only 91%. While for SL the perception rate (88%) is worse than the recognition rate in the previous test (94%). Furher investigations have to show if these two patterns for the movement instructions bending and stretching legs are sufficient or need to be improved.

5.3 Universality of the Designed Patterns

The results of the previous described experiments show that tactile full-body movement instruction are perceived and identified with high accuracy even under cognitive and physical demanding tasks. This prompted us to explore these tactile instructions in a real environment.
We will repeat the learnability experiment while subjects ride a horse. It is of interest to us if horse riders perceive the tactile instructions when the horse is in the walk or in the trot. The commotion produced by the horse could effect the perception of the tactile stimuli.
Although horse riding is a cognitive and physical demanding activity we believe that this does not hinder the perception and identification as the cognitive and physical load is low in comparison with other sport activities.

Figure 5.15: Horse rider with tactile equipment

5.3.1 Subjects

Eight horse riders aged between 12 and 37 years participate in this user test. All participants are female. On a scale raging from level 1 (beginner) to level 5 (expert), four subjects rate their skills as advanced beginners (level 2), one as advanced (level 3), and three as proficient (level 4). Subjects practice horse riding weekly.
One of the participants has previous experience with tactile feedback as she took part in a lab user test. None of the subjects report any sensory difficulties.

5.3.2 Procedure

The experiment is conducted in an indoor riding ring or outdoor riding ring depending on the weather conditions. The riding ring is also used by other riders during the test. To attach the vibration motors subjects have to wear the cycling shorts and the tight fitting shirt over their normal riding clothing. The SensAct boxes are put in a backpack, which the subjects also have to wear (see figure 5.15). As in the previous tests tactile patterns for the upper body and legs are tested separately. In the test only these tactile movements instructions are tested that make sense in horse riding (c.f. 4.1.3—“Horse Riding”). During the test the tactile movement instructions are delivered that are listed in table 5.9.

Lean Forward (LF)	$R_U(BMB)$
Lean Backward (LB)	$R_U(FMB)$
Lean Left (LL)	$R_U(LRB)$
Lean Right (LR)	$R_U(LLB)$
Take Shoulders Backward (TSB)	$SP\_P(CB)$
Straighten Legs (SL)	$SP\_R_U(FLT, FRT)$
Bend Legs (BL)	$SP\_R_U(BLT, BRT)$
Shift weight left (SWL)	$R_U(LRT)$
Shift weight right (SWR)	$R_U(LLT)$

Table 5.9: Tactile movement instructions given to the horse riders

After attaching the vibration motors to the clothing of the upper body or legs, the participants are familiarized with the patterns for the corresponding body part. Each pattern is triggered two to three times. When the riders are certain that they learned each assignment of a tactile pattern to a specific movement instruction the user test starts.

Participants are asked to first keep the horse in the walk and subsequently in the trot. While riding in the walk or in the trot the subjects are given the different tactile patterns two times in a randomized. After perceiving a pattern the subjects are requested to say aloud the corresponding movement instruction.

After the test subjects had to fill out a questionnaire, see C—“Questionnaire of the Horse Riding Test” for comparison.

5.3.3 Results

Figure 5.16 shows the results for the recognition rates during the walk and trot.
All recognition rates are clearly above chance level, which is 20% for the upper body and 25% for the legs.

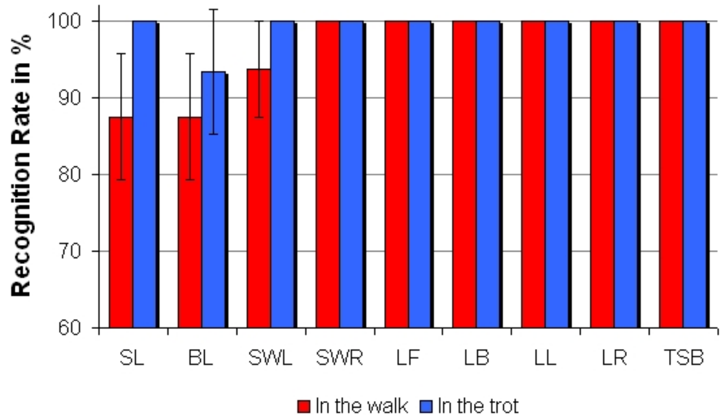


Figure 5.16: Percentage of recognized patterns while horse riding (with standard error)

The patterns for the upper body are always correctly recognized by the participants both in the walk and in the trot. The recognition rate for the movement instructions for the legs are worse. The recognition rate in the trot for those patterns is equal or better than in the walk. Shifting wight to the right is identified with 100% accuracy in both gaits while SWL is identified with 100% accuracy only in the trot. For the patterns SL and BL the recognition rate in the walk is 88% and in the trot between 93% for BL and 100% for SL. Participants confound the meaning of the patterns for the legs, while the perception is alright.

Figure 5.17 shows the ratings for the tactile movement instructions.

The ratings indicate that the perception of the tactile patterns is good, the sensation is somewhat pleasant, and that participants could very often map body movements to the tactile instructions. Only patterns delivered at the back or front of the upper body of the subjects are not perceived very good.

The subjects agree that the patterns for tactile instructions are intuitive. One subject states that the tactile instructions for the upper body are better than those for the legs concerning their intuitiveness. Through the tactile feedback they feel incited to perform the corresponding movement. Most of the subjects disagree that the tactile feedback dis-

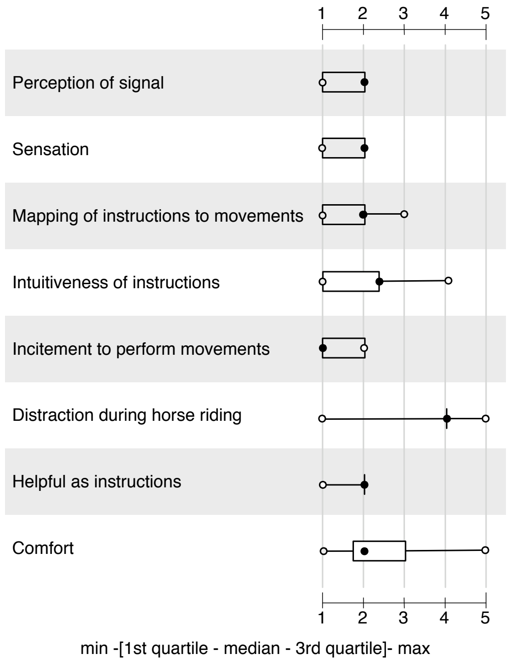


Figure 5.17: Results of the post-test interview for tactile movement instructions

tracts them from horse riding. One participant states that she is distracted, because the focus is changed from the horse to the riders posture.
Finally all subjects agree that the tactile feedback will be helpful for movement instructions during horse riding but the hardware setup has to change. All participants do not like to wear the backpack during horse riding but to wear the clothes together with the vibration motors is alright.

5.3.4 Discussion

The user test points out that the designed patterns work in an intuitive and/or learnable way in a real application like horse riding. The results show that the recognition rate is for nearly all patterns 100% in the walk and in the trot. This indicates that the vibration motor frequency is sufficient for horse riding activities.
As the participants are first tested in the walk and then in

the trot, the worse results in the walk for patterns for the legs can be explained by that participants are still in the learning phase for those patterns. These denotes that the patterns for the legs are less intuitive. The patterns are tested before only while the subjects are standing. It is possible that the mappings are different while the person stands or sits. This will need further investigations.
Another possible reason one subject states is that the posture mistakes for the legs are beginner mistakes, while those for the upper body even advanced riders do.

The participants of this user test believe that tactile feedback would be helpful in supporting them in improving their riding posture. During normal riding the horse riders try to improve the gaits of the horse or to ride variations of track figures. In these situations the riders posture is eclipsed. The tactile cues will remind the rider to also take care of his own posture.
Some of the participants claim that the tactile feedback system could replace the riding instructor, if the tactile feedback will be further improved and refined to map every horse riding movement, which is dependent on the gait of the horse as well as on the track figures.

During the user test the user's full attention was directed on the tactile patterns as the subjects are advanced beginners or proficient in horse riding. So further investigations should concentrate on recognition rates when the user's attention is not on the tactile feedback, for example in a riding lesson. These investigations will give distinctiveness if the tactile feedback is able to remind the rider of his posture without directing his attention away from his primary focus.

The worse perception of the tactile feedback on the front and back of the upper body can be explained by the physique of the subjects, which are all female. Instead of having one line of vibration motors on the front and back, it could be beneficial to use two parallel lines to overcome the deepening by the spine and between the breast.

5.4 Conclusion

During the preceding user tests the tactile design was continuously improved.

Thus the final results reveal that participants are able to associate movement instructions with tactile patterns with high accuracy. Even under cognitive load conditions the posture correction is recognized properly. These patterns function on a local basis that means that vibrations take place on the body locations that are directly involved in the posture correction.

For indication of movement instruction participants prefer rabbit patterns over one-element patterns as they do not only provide the information which body part is affected but also provide a directional cue.
It has to be mentioned that preferring rabbit patters is not dependent on the body location as it is always preferred. Only for taking shoulders backward a simultaneous one-element pattern is used. This may result from the fact that taking shoulders backwards is a very common movement and the countermovement has no relevance in everyday life or sports. In nearly all domains it is required to keep the shoulders straight.

Further investigations in rabbit patterns showed that single rabbit patterns and "Geldard" rabbit patterns are inferior to the standard rabbit pattern used in this thesis. The standard rabbit pattern vibrates three times at the first and second body location and once at the third. Thereby it provides enough time to identify the pattern.

Simple rabbit pattern

The employed patterns for indicating movement instructions have to be kept as simple as possible. Simple rabbit patterns are mostly preferred over compound or simultaneous rabbit patterns like, for example, for shifting weight. Simultaneous patterns regardless of being simultaneous one-element patterns or simultaneous rabbit patterns require longer processing times to detect the location and direction they indicate. This reduces the recognition rate especially under cognitive load.
Furthermore simultaneous rabbit patterns can evoke con-

fusions as the vibration is judged as being too strong and unpleasant.

During the tactile design it was decided to use the "push"-metaphor. Although half of the participants find the "pull"-metaphor more intuitive, recognition rates of 100% for the lean-patterns (LF, LB, LL, LR) in relaxed and cognitive load condition demonstrate that the push-metaphor is easy to learn. Therefore a movement instruction language does not have to be adopted to these preferences.

The investigation in the movement instruction for turning the upper body is not yet concluded. The two explored turn pattern types (rotational and diagonal rabbit patterns) do not lead to good identification rate as either the direction of the required turn is not perceived or the pattern is confounded with other patterns of the upper body that share the same vibration motors.
For future work another alternative has to be explored to overcome both kinds of problems. This alternative can, for example, be a horizontal rabbit pattern ($R_L(FCB)$, $R_R(FCB)$), which was previously tested as a possible leaning pattern. The results revealed that some participants felt incited to turn the upper body instead of leaning the upper body to the side.

All results reveal that it is very well possible to inherently associate movements with specific patterns. In table 5.10 the resulting associations of tactile patterns to movement instructions are listed.

As previously hypothesized the designed patterns require minimum training and their identification rate does not decrease considerably under cognitive load.
The overall recognition rate for those patterns is more than 95% in relaxed condition when using the rotational rabbit patterns, which both start at the same body location. In the cognitive condition the overall recognition rate is slightly decreased to about 94%.
As a conclusion the developed patterns are intuitive or at least learnable in their field of application. The user test in the field demonstrates the functionality under real world conditions.

LF	$R_U(BMB)$
LB	$R_U(FMB)$
LL	$R_U(LRB)$
LR	$R_U(LLB)$
TSB	$SP\_P(CB)$
SLA	$R_D(BLA) + P^3(FRA)$
SRA	$R_D(BRA) + P^3(FLA)$
TL	$(R_L(FMB, LLB, BMB, LRB))^2$
TR	$(R_R(FMB, LRB, BMB, LLB))^2$
BL	$SP\_R_D(BLT, BRT)$
SL	$SP\_R_U(FLT, FRT)$
SWL	$R_U(LRT)$
SWR	$R_U(LLT)$

Table 5.10: Resulting tactile patterns for movement instructions

In this thesis we have developed tactile patterns, see table 5.10, for basic movements instructions that as basic elements of a tactile language.
We have given a structure in which way patterns can be combined to transmit even more complex information. Further user tests have to show which ways of combining basic patterns to complex patterns are most effective. According to direct speech the complex instructions consist of basic instructions which are given successively. Our investigations have shown that people prefer compound patterns over simultaneous patterns for basic instructions. Further investigations will have to show if the recognition rate is comparable for complex movement instructions or if new types of combination are required.

Chapter 6

Summary and Future Work

"Dustfinger inspected his reddened fingers and felt the taut skin. "He might tell me how my story ends", he murmured. Meggie looked at him in astonishment. "You mean you don't know?" Dustfinger smiled. Meggie didn't particularly like this smile. "What's so unusual about that, princess?" he asked quietly. "Do you know how your story ends?" Meggie had no answer to that."

— Cornelia Funke, Inkheart

6.1 Summary and Contributions

In this thesis we presented a new way to make use of full-body tactile feedback. The tactile feedback is designed as an alternative to other senses or to supplement them to correct body posture. Therefore we first outlined the advantages of tactile feedback over visual and auditory feedback. The previous work supported us in our own design of tactile patterns and in the attempt to build a tactile language for movement instructions. In the same way the previous work reveals additional domains for further investigation.

Before we designed the tactile patterns we identified new domains for which tactile feedback for body posture correction would be beneficial. We have chosen two daily activities (sedentary work and carrying heavy goods) and two sport domains (horse riding and nordic walking) as representative application. From these domains we filtered those movements that are common in all domains and can therefore be considered as "universal" or basic body movements, see table 4.1 for comparison. For those movements the tactile patterns were designed.

For the tactile design we decided to use the tactile parameters body location and frequency. In a pilot test we determined which body locations are appropriate and at which frequency the vibration motors should be operated for good perception of the tactile feedback. The body locations and the duration of the vibration were determined by the characteristics of sensory saltation, which gives the user directional cues for the posture correction.

To provide a basis for the tactile patterns we first defined a structure of a tactile language. The basic elements of this tactile language are one-element patterns that means vibrations on a single body location. These one-element patterns can be combined simultaneously or successively. The directional cues, for example, are built by successively combining three one-element patterns. This pattern is called a rabbit pattern.

Based on the structure of this language we designed different tactile patterns which are meant to indicate body posture corrections. In order to validate our design we performed a user test in which the participants were invited to say what they would intuitively associate with a given tactile pattern. After this user test we were able to inherently associate specific patterns with specific movement instructions.

Through this first test about the intuitivity of the designed patterns we found out that patterns should always be given at the distinct location where the body posture correction is needed. Furthermore we found out that tactile patterns that contain directional cues (rabbit patterns) are favored by the participants over one-element patterns.

In the next test we examined if the association of tactile patterns to specific movement instructions can be learned and if these association are also remembered in a cognitive de-

manding task. Therefore we performed a user test which consisted of a training phase, a test phase without cognitive load, and a test phase with cognitive load. The test revealed that users are able to interpret and apply our tactile movement instruction patterns both in relaxed condition and under cognitive load. We obtained a overall recognition rate of 94%.
Finally we tested a selection of our designed tactile movement instructions under real-world conditions. Therefore we have chosen one of the previously identified sport applications (horse riding). The participants had to give feedback about the perceived patterns in different situations after a short learning period. Again the participants were able to distinguish the tactile movement instructions with high accuracy.
During the whole evaluation the tactile design was continuously improved. In relaxed condition the overall identification accuracy of the tactile movement instructions is 95% while it is slightly decreased in the cognitive demanding condition.

Our results of this thesis confirm that tactile feedback is an appropriate instrument to give information about the actual body posture even during physical activities. While doing so rabbit patterns are favored as they do not only indicate the body location which is affected by the movement but also the direction of the movement. Universal tactile patterns on the basis of rabbit patterns achieve high recognition accuracy even under physical and cognitive demanding conditions.

6.2 Future Work

Although with this thesis the basis for a intuitive tactile movement instruction language is founded, there are some topics which should be treated in future work.

First of all new basic movement instructions should be identified to prove that the obtained results are also applicable to other movement instructions. Furthermore the designed patterns have to be tested in other sport and daily domains besides horse riding. Another step could be to combine the tactile feedback with an automatic error detection through sensors to find out in which way the tactile instructions have to be combined to give complex movement instructions.

Another considerations is to use variations in frequency or intensity to indicate the severity of the required posture error. At the moment we use the tactile parameters duration and body location to encode the movement instruction. It has to be shown if using an additional parameters would be a benefit for the tactile movement instruction language or if this complicates the pattern recognition.

Furthermore the patterns for turning the upper body as well as the patterns for legs need further improvement. For turning the upper body a horizontal pattern should be considered. The patterns for the movement instructions of bending and straightening legs and shifting weight should be further explored while the participants sit. So far we tested the patterns exclusively while the participants are standing. In the horse riding test we obtained 100% identification accuracy for the patterns of the upper body, while those for legs are more often confounded.

Moreover in future research there are possibilities to improve the garment design. By sewing or manufacturing the tactors and their wiring directly into the clothing itself, the process of putting on the tactor suit would be gradually simplified.
Furthermore we have identified that subjects have problems in recognizing vibrations on the chest and at the back. This recognition could be improved by using parallel lines of vibration motors at the front and back of the torso. While doing so new problems could arise when patterns which use body location at the lateral side of the body or at the collarbone are confounded with those at the chest or back.

Another application for the presented patterns which was not explored in this thesis is the use during learning of sport disciplines. The presented results allow the conclusion that tactile feedback can accelerate the learning process.

Appendix A

List of Abbreviations

BL	Bend the legs
LB	Lean upper body backward
LF	Lean upper body forward
LL	Lean upper body to the left
LR	Lean upper body to the right
SWL	Shift weight left
SWR	Shift weight right
SL	Straighten the legs
SLA	Swing left arm forward and right arm backward
SRA	Swing right arm forward and left arm backward
TS	Take shoulders backward
TL	Turn to the left
TR	Turn to the right

Table A.1: List of movement instruction abbreviations

BLA	Back left arm
BLT	Back left thigh
BMB	Back middle body
BRA	Back right arm
BRT	Back right thigh
FCB	Front chest body
FHB	Front hip body
FLA	Front left arm
FLT	Front left thigh
FMB	Front middle body
FRA	Front right arm
FRT	Front right thigh
FS	Front shoulder
FWB	Front waist body
LBF	Left ball of the foot
LHK	Left hollow of the knee
LLA	Lateral left arm
LLB	Lateral left body
LLT	Lateral left thigh
LP	Left palm
LRA	Lateral right arm
LRB	Lateral right body
LRT	Lateral right thigh
LSF	Left sole of foot
RBF	Right ball of the foot
RHK	Right hollow of the knee
RSF	Right sole of foot
RP	Right Palm

Table A.2: List of body location abbreviations

Appendix B

Questionnaire for User Tests in the Lab

Questionnaire – Tactile Patterns

Date: ______________________

Time: ______________________

Personal data

Age: _______

Gender: [ ] male / [ ] female

Profession: ______________________________

Do you have any disease, that could handicap your tactile perception?

[ ] Yes / [ ] No

Do you practice any of the following sport activities?

Snowboarding: [ ] Yes / [ ] No

Nordic Walking: [ ] Yes / [ ] No

Horse Riding: [ ] Yes / [ ] No

Others: ____________________________

Did you already gain experience with tactile feedback?

[ ] Yes / [ ] No

Figure B.1: Standard questionnaire for user tests in the lab

Appendix C

Questionnaire of the Horse Riding Test

Questionnaire – Tactile Patterns – Horse Riding

Date: ________________________
Time: ________________________

Personal data

Age: _______
Gender: [ ] male / [ ] female
Profession: ____

Do you have any disease, that could handicap your tactile perception?
[ ] Yes / [ ] No

Do you practice Horse Riding: [ ] Yes / [ ] No

I would grade my riding skills as:

[ ] beginner
[ ] advanced beginner
[ ] advanced
[ ] proficient
[ ] expert

Did you already gain experience with tactile feedback?
[ ] Yes / [ ] No

Figure C.1: Questionnaire of the horse riding user test - page 1

Tactile feedback

1.) I could perceive the tactile feedback during horse riding:

[ ] Very Good
[ ] Good
[ ] Barely Acceptable
[ ] Poor
[ ] Very Poor

2.) The sensation of tactile feedback was:

[ ] Very pleasant
[ ] Somewhat pleasant
[ ] Neither pleasant nor unpleasant
[ ] Somewhat unpleasant
[ ] Very unpleasant

3.) I could map tactile instructions to body movements:

[ ] Always
[ ] Very Often
[ ] Sometimes
[ ] Rarely
[ ] Never

4.) Tactile instructions were intuitive:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

Figure C.2: Questionnaire of the horse riding user test - page 2

5.) Having perceived tactile feedback, I felt incited to perform the movement:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

6.) Tactile feedback distracts from focusing on horse riding:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

7.) For instructions during horse riding, I think tactile feedback is helpful:

[ ] Strongly Agree
[ ] Agree
[ ] Undecided
[ ] Disagree
[ ] Strongly Disagree

Overall impression

8.) Wearing the system was...

[ ] Very comfortable
[ ] Somewhat comfortable
[ ] Neither comfortable nor uncomfortable
[ ] Somewhat uncomfortable
[ ] Very uncomfortable

Figure C.3: Questionnaire of the horse riding user test - page 3

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Index