

A Language of Tactile Motion Instructions for Physical Activities

Von der Fakultät für Mathematik, Informatik und
Naturwissenschaften der RWTH Aachen University
zur Erlangung des akademischen Grades eines
Doktors der Naturwissenschaften genehmigte Dissertation

vorgelegt von

Dipl.-Inform. Daniel Spelmezan

aus Bistrița, Rumänien

Berichter: Prof. Dr. Jan Borchers
Prof. Dr. Martina Ziefle

Tag der mündlichen Prüfung: 28. Juni 2011

Contents

| | |
|--|--------------|
| Abstract | xvii |
| Überblick | xix |
| Acknowledgements | xxi |
| Conventions | xxiii |
| 1 Introduction | 1 |
| 1.1 Tactile Instructions Correct Wrong Posture | 2 |
| 1.2 Context and Scope of this Thesis | 3 |
| 1.2.1 Visual and Audio Feedback | 4 |
| 1.2.2 Tactile Feedback and Force Feedback | 5 |
| 1.2.3 Outlook | 6 |
| 1.3 Thesis Contributions | 7 |
| 1.4 Thesis Structure | 8 |
| I Wearable Sensing and Feedback Devices | 11 |
| 2 Wearable Computing | 13 |
| 2.1 Wearable Computers | 13 |
| 2.2 Context-Awareness | 14 |

| | | |
|----------|--|-----------|
| 2.3 | Toolkits for Building Wearable Computing Applications . . . | 16 |
| 2.3.1 | Sensing Devices and Prototyping Platforms | 16 |
| 2.3.2 | Software Toolkits for Sensor Data Analysis | 19 |
| 2.3.3 | Tactile Feedback Devices | 19 |
| 2.4 | Iterative Design: A Challenge in Designing Wearable Computing Applications | 20 |
| 2.5 | Closing Remarks | 22 |
| 3 | A Wearable Sensing and Feedback System | 23 |
| 3.1 | Hardware Platform | 23 |
| 3.1.1 | The SensAct Box | 24 |
| 3.1.2 | The Mobile Host Device | 27 |
| 3.2 | Software Tools | 27 |
| 3.2.1 | Sensor Monitor and Motor Control | 27 |
| 3.2.2 | iSense | 28 |
| 3.2.3 | Tactile Editor and SensAct Control | 29 |
| 3.3 | Closing Remarks | 30 |
| 4 | Towards a Wearable Snowboarding Assistant | 33 |
| 4.1 | Interviews with Snowboard Instructors | 34 |
| 4.2 | Common Mistakes in Snowboarding | 36 |
| 4.3 | Initial Testing of the Technology | 38 |
| 4.3.1 | Hardware and Sensor Setup | 38 |
| 4.3.2 | Participants and Study Procedure | 40 |
| 4.3.3 | Preliminary Results | 41 |
| 4.3.4 | The Instructors' Opinion | 43 |
| 4.4 | Sensing Basic Context Information While Snowboarding . . . | 44 |

| | | |
|---|--|-----------|
| 4.4.1 | Hardware Setup | 45 |
| 4.4.2 | Participants and Study Procedure | 46 |
| 4.4.3 | Classification of the Riding Edge and of Turns | 46 |
| | Results | 48 |
| | Discussion | 50 |
| 4.4.4 | Knee Flexion during the Ride | 51 |
| | Results | 53 |
| | Discussion | 54 |
| 4.4.5 | Activity Recognition: Riding and Pausing | 54 |
| | Results | 55 |
| | Discussion | 55 |
| 4.5 | Closing Remarks | 56 |
| II Tactile Motion Instructions | | 57 |
| 5 Fundamentals of Tactile Perception | | 59 |
| 5.1 | The Cutaneous Sense | 59 |
| 5.2 | Tactile Display Technologies | 62 |
| 5.3 | Parameters for Tactile Information Transfer | 64 |
| 5.4 | Applications for Tactile Feedback | 68 |
| 5.4.1 | Sensory Substitution | 68 |
| 5.4.2 | Navigation Systems | 69 |
| 5.4.3 | Warning Signals | 70 |
| 5.4.4 | Interaction with Mobile Devices | 71 |
| 5.4.5 | Distant and Emotional Communication | 72 |
| 5.4.6 | Virtual Reality | 72 |

| | | |
|----------|--|-----------|
| 5.5 | Closing Remarks | 73 |
| 6 | Tactile Motion Instructions | 75 |
| 6.1 | Informing the Design | 77 |
| 6.1.1 | Expressive Sensations | 78 |
| 6.1.2 | Stimulus Duration and Perception under Workload . | 79 |
| 6.1.3 | Stimulus Locations on the Body | 81 |
| 6.1.4 | A Notation for Tactile Patterns | 82 |
| 6.1.5 | Tactile Suit and Hardware Setup | 83 |
| 6.2 | Intuitive Interpretation of Tactile Stimuli | 86 |
| 6.2.1 | Participants and Experimental Setup | 87 |
| 6.2.2 | Results | 87 |
| 6.2.3 | Discussion | 89 |
| 6.2.4 | First Design Recommendations | 91 |
| 6.3 | Tactile Motion Instructions in Stationary and in Active Situations | 94 |
| 6.3.1 | Perception under Increasingly Realistic Conditions . | 94 |
| | Participants and Experimental Setup | 95 |
| | Results | 97 |
| | Discussion | 101 |
| 6.3.2 | Perception under Real-World Conditions: Snowboarding | 102 |
| | Participants | 103 |
| | Hardware Setup | 103 |
| | Experimental Setup | 104 |
| | Results | 105 |
| | Discussion | 109 |

| | | |
|----------|---|------------|
| 6.3.3 | Perception under Real-World Conditions: Horseback Riding | 110 |
| | Participants and Hardware Setup | 111 |
| | Experimental Setup | 112 |
| | Results | 112 |
| | Discussion | 114 |
| 6.3.4 | Revised Design Recommendations | 115 |
| 6.4 | Instructions for Upper Body Rotation | 116 |
| 6.4.1 | Participants | 117 |
| 6.4.2 | Experimental Setup | 118 |
| 6.4.3 | Results | 119 |
| 6.4.4 | Discussion | 120 |
| 6.5 | Preliminary Design Recommendations | 121 |
| 6.6 | Closing Remarks | 124 |
| 7 | A Language of Tactile Motion Instructions | 127 |
| 7.1 | Tactile Languages | 128 |
| 7.1.1 | Characters as Basic Elements | 128 |
| 7.1.2 | Words as Basic Elements | 129 |
| 7.1.3 | A Tactile Language for Physical Activities | 130 |
| 7.2 | Compound Tactile Motion Instructions | 130 |
| 7.2.1 | Participants and Experimental Setup | 133 |
| 7.2.2 | Results | 136 |
| 7.2.3 | Discussion | 141 |
| 7.3 | Characteristics of Tactile Motion Instructions | 144 |
| 7.3.1 | Participants and Experimental Setup | 145 |

| | | |
|----------|--|------------|
| 7.3.2 | Results | 147 |
| 7.3.3 | Discussion | 150 |
| 7.4 | Closing Remarks | 152 |
| 8 | Learning Motor Skills | 153 |
| 8.1 | Feedback in Motor Skill Learning | 154 |
| 8.2 | Concurrent Tactile Motion Instructions for Learning Motor Skills in Snowboarding | 156 |
| 8.3 | Experimental Setup | 159 |
| 8.3.1 | Hardware Setup | 160 |
| 8.3.2 | Pilot Test with Snowboard Instructor | 161 |
| 8.3.3 | Participants | 163 |
| 8.3.4 | Experimental Procedure | 164 |
| 8.4 | Results | 166 |
| 8.4.1 | Classification of the Riding Edge | 166 |
| 8.4.2 | The Participants' Riding Skills (Video Analysis) | 170 |
| | Riding Mistakes | 170 |
| | Quality of Descents | 171 |
| | Individual Progress | 173 |
| 8.4.3 | The Participants' Opinion (Questionnaire Results) | 174 |
| 8.5 | Discussion | 177 |
| 8.5.1 | The Wearable System | 177 |
| 8.5.2 | Video Analysis and Questionnaire Results | 179 |
| 8.5.3 | Study Limitations | 182 |
| 8.6 | A General Set of Tactile Motion Instructions | 184 |
| 8.7 | Design Recommendations for Tactile Motion Instructions | 190 |

| | |
|--|------------|
| 8.8 Closing Remarks | 192 |
| III Conclusion | 193 |
| 9 Conclusions | 195 |
| 10 Future Work | 199 |
| 10.1 Wearable Computing | 199 |
| 10.2 Tactile Motion Instructions | 200 |
| 10.3 Motor Learning | 202 |
| IV Appendix | 205 |
| A Motor Shield Schematic | 207 |
| B Post-Study Questionnaire: Comparing Tactile Instructions to Audio Instructions While Snowboarding | 209 |
| C Post-Study Questionnaire: Perception of Tactile Instruc- tions While Horseback Riding | 213 |
| D Post-Study Questionnaire: Learning New Motor Skills | 217 |
| E The Structure of Languages | 223 |
| Bibliography | 225 |
| Index | 245 |
| Publications | 253 |
| Curriculum Vitae | 255 |

List of Figures

| | | |
|-----|---|----|
| 1.1 | Tennis versus snowboard lessons | 2 |
| 1.2 | The Ski Coach. | 5 |
| 1.3 | ACM SIGCHI Curricula for HCI | 8 |
| 2.1 | XSens MTx motion capture device and MVN suit | 16 |
| 2.2 | Shake SK6 and Arduino BT | 17 |
| 2.3 | TactaBoard and TactaVest | 19 |
| 2.4 | Iterative design | 20 |
| 3.1 | System architecture of the wearable platform | 24 |
| 3.2 | The first sensor box | 25 |
| 3.3 | The custom-built motor shield | 25 |
| 3.4 | The second prototype of the SensAct box | 26 |
| 3.5 | The final SensAct box | 26 |
| 3.6 | iSense Mobile Software | 28 |
| 3.7 | iSense Software | 28 |
| 3.8 | Tactile Editor Software | 29 |
| 3.9 | SensAct Control Software | 30 |
| 4.1 | Snowboard terminology | 36 |
| 4.2 | Neutral position, frontside turn, backside turn | 36 |

| | | |
|------|--|----|
| 4.3 | Correct posture for basic turns | 37 |
| 4.4 | Typical snowboarding mistakes | 37 |
| 4.5 | Bend sensors at the knees | 39 |
| 4.6 | Setup of pressure sensors | 39 |
| 4.7 | The sensing system for the first field study | 40 |
| 4.8 | Raw force sensor values while snowboarding | 41 |
| 4.9 | Raw bend sensor values while snowboarding | 42 |
| 4.10 | Optical bend sensor | 45 |
| 4.11 | Classification of turns while snowboarding | 49 |
| 4.12 | Raw optical bend sensor values while snowboarding | 52 |
| 4.13 | Classification of knee flexion and of the riding edge while snowboarding | 53 |
| 4.14 | Raw accelerometer values while snowboarding | 55 |
| 5.1 | Cross section of the skin | 60 |
| 5.2 | Vibration motors | 63 |
| 5.3 | Sensory saltation | 66 |
| 5.4 | Braille displays | 69 |
| 6.1 | The design space of mobile tactile interfaces | 78 |
| 6.2 | Timing values for tactile stimuli | 81 |
| 6.3 | The position of vibration motors on the body | 81 |
| 6.4 | The first design of the tactile suit | 84 |
| 6.5 | A cylindrical vibration motor inside a tube | 84 |
| 6.6 | Vibration frequency range of the Nokia 3270 vibration motor | 85 |
| 6.7 | The first set of tactile motion instructions: push metaphor | 93 |
| 6.8 | A participant on the Wii balance board | 95 |

| | | |
|------|---|-----|
| 6.9 | Percentage of recognized instructions in the laboratory, group A | 99 |
| 6.10 | Percentage of recognized instructions in the laboratory, group B | 99 |
| 6.11 | A snowboarder with a backpack | 103 |
| 6.12 | Percentage of recognized instructions while snowboarding . | 106 |
| 6.13 | Likert scale ratings of instructions while snowboarding . . . | 107 |
| 6.14 | Correct posture while riding a horse | 111 |
| 6.15 | Percentage of recognized instructions while riding a horse . | 112 |
| 6.16 | Likert scale ratings of instructions while riding a horse . . . | 113 |
| 6.17 | Alternative tactile patterns for upper body rotation | 116 |
| 6.18 | Revised set of tactile motion instructions: pull metaphor . . | 122 |
| 6.19 | Alternative set of tactile motion instructions: pull metaphor | 123 |
| 7.1 | Tactile motion instructions: pull metaphor | 134 |
| 7.2 | Tactile motion instructions: push metaphor | 135 |
| 7.3 | Percentage of recognized basic instructions in the stationary situation | 138 |
| 7.4 | Percentage of recognized basic instructions in the active situation on the Wii balance board | 139 |
| 7.5 | Percentage of recognized compound instructions in the stationary situation | 140 |
| 7.6 | Percentage of recognized compound instructions in the active situation on the Wii balance board | 140 |
| 7.7 | Intuitive interpretation of tactile motion instruction patterns | 147 |
| 7.8 | Learning and long-term recall of tactile motion instructions | 149 |
| 8.1 | The position of vibration motors on the body during the snowboarding course | 157 |
| 8.2 | Tactile motion instructions for pivoting the snowboard. . . | 158 |

| | | |
|------|--|-----|
| 8.3 | Setup of pressure sensors during the snowboarding course | 160 |
| 8.4 | Reduced timing values for tactile stimuli | 162 |
| 8.5 | Pivoting the board during turns | 167 |
| 8.6 | The estimated period when tactile motion instructions were perceived during turns. | 169 |
| 8.7 | The participants' grading of their own snowboarding skills | 175 |
| 8.8 | Likert scale ratings of instructions applied during the snowboarding course | 176 |
| 8.9 | Likert scale ratings of instructions for learning new riding techniques | 177 |
| 8.10 | The final set of tactile motion instructions: pull metaphor | 184 |
| 8.11 | The final set of tactile motion instructions: push metaphor | 186 |
| 8.12 | Tactile motion instructions in the design space of mobile tactile interfaces | 189 |
| A.1 | Motor shield schematic | 208 |

List of Tables

| | | |
|-----|---|-----|
| 4.1 | Percentage of recognized turns while snowboarding | 49 |
| 5.1 | Characteristics of mechanoreceptors | 60 |
| 6.1 | Three-letter acronyms for the position of actuators on the body | 82 |
| 6.2 | Percentage of concrete responses to tactile patterns | 87 |
| 6.3 | Frequent responses to tactile patterns | 88 |
| 6.4 | Ten body movements as instructions | 92 |
| 6.5 | Percentage of recognized instructions in the laboratory . . . | 97 |
| 6.6 | Number of participants who misinterpreted instructions . . | 100 |
| 6.7 | Wording of instructions while snowboarding | 104 |
| 6.8 | Tactile patterns for upper body rotation | 117 |
| 6.9 | Preferred tactile patterns for upper body rotation | 119 |
| 7.1 | Preference to being pulled and pushed (1) | 136 |
| 7.2 | Percentage of recognized basic and compound instructions in the laboratory | 137 |
| 7.3 | Number of participants who misinterpreted basic instructions | 138 |
| 7.4 | Number of participants who misinterpreted compound in- structions | 139 |
| 7.5 | Preference to being pulled and pushed (2) | 147 |

| | | |
|-----|---|-----|
| 7.6 | Intuitive interpretation of tactile motion instruction patterns | 148 |
| 8.1 | Percentage of recognized turns during the snowboarding course | 168 |
| 8.2 | The participants' skills in riding switch | 170 |
| 8.3 | Number of falls during the snowboarding course | 170 |
| 8.4 | Percentage of riding mistakes during the snowboarding course | 172 |
| 8.5 | Summary of the participants' riding skills during the snow- boarding course and their view on tactile motion instructions | 178 |
| 8.6 | Preference to being pulled and pushed (3) | 190 |

Abstract

Athletes benefit from immediate and frequent feedback on their performance during training. Therefore, coaches try to provide instructions and feedback over multiple sensory channels before, during, and immediately after an exercise: they explain and demonstrate how to move the body, and they move the athletes' bodies into correct position. In many situations, however, athletes only receive feedback after performing an exercise because they are spatially separated from their coaches. Also, they do not experience tactile feedback through the coaches' hands.

To overcome these limitations, this work proposes and investigates artificial tactile stimuli for providing instructions and feedback on performance in realtime. These tactile signals are called tactile motion instructions. They stimulate specific body locations to communicate how to move and how to adjust the posture. Empirical studies conducted in static and in active situations informed the iterative design and the evaluation of a general set of tactile motion instructions that can represent body movements in an intuitive way. These tactile instructions can be perceived and recognized with high accuracy in situations that are cognitively and physically demanding. In particular, they can lead to faster response times to move the body than spoken instructions that are conveyed over earplugs.

Tactile motion instructions constitute a simple language where sequentially triggered instructions can guide athletes during sequences of body movements. Using snowboarding as an example, a field study conducted with snowboarders who experienced tactile motion instructions while practicing a new riding technique demonstrated that this tactile language can help athletes to learn motor skills.

This work is the first investigation into the intuitive interpretation of full-body tactile stimuli that can instruct how to move the body during physical activities. The insights into the perception and recognition of these stimuli in stationary and in active situations lead to guidelines for designing tactile motion instructions. Besides sports training, the findings from this research can be applied to various domains where immediate feedback on incorrect posture is typically missing or impracticable, such as to prevent injuries in unsupervised situations during daily physical activities, or to enhance rehabilitative exercises for regaining lost motor skills.

This dissertation also presents a custom-built wearable and wireless sensor and actuator system. This system enabled the design of tactile motion instructions and their evaluation in real-world conditions, and demonstrated that sensing and classifying posture and body movements while snowboarding is possible in realtime. This system resulted in the first wearable assistant for snowboard training that automatically provided tactile motion instructions during descents.

Überblick

Sportler profitieren während des Trainings von unmittelbarer und häufiger Rückmeldung zu ihrer Leistung. Aus diesem Grund versuchen Trainer Anweisungen und Rückmeldung vor, während, und unmittelbar nach einer Übung zu geben, und zwar über mehrere Sinneskanäle: Sie erklären und demonstrieren die korrekte Ausführung der Bewegungen, und sie helfen dem Sportler per Hand, den Körper in die richtige Stellung zu bringen. Allerdings sind Sportler in vielen Situationen räumlich von ihren Trainern entfernt, so dass sie Rückmeldungen nur nach der Übung erhalten. Des Weiteren erfahren sie keine taktile Rückmeldung durch die Berührung der Trainer.

Diese Dissertation untersucht, wie künstliche taktile Reize Anweisungen und Rückmeldung während der Ausführung physischer Aktivitäten geben können. Diese taktilen Reize werden taktile Bewegungsanweisungen genannt. Sie stimulieren bestimmte Körperstellen um zu vermitteln, wie man sich bewegen und wie man die Körperhaltung korrigieren soll. In mehreren empirischen Untersuchungen wurde untersucht, welche Körperbewegungen sich durch taktile Bewegungsanweisungen intuitiv repräsentieren lassen und wie diese Reize wahrgenommen werden. Diese Untersuchungen wurden mit entspannter Körperhaltung und während der Ausübung physisch und kognitiv belastender Aktivitäten durchgeführt. Die Ergebnisse zeigen, dass die entworfenen taktilen Bewegungsanweisungen mit hoher Genauigkeit wahrgenommen und erkannt werden können. Insbesondere können sie zu schnelleren Reaktionszeiten führen als über Kopfhörer übermittelte Sprachanweisungen.

Taktile Bewegungsanweisungen bilden eine einfache Sprache, in der eine Folge von Bewegungsanweisungen eine Abfolge von Körperbewegungen repräsentieren kann. In einer Feldstudie mit Snowboardfahrern wurde demonstriert, dass diese taktile Sprache beim Erlernen motorischer Fähigkeiten helfen kann. Dazu wurden taktile Bewegungsanweisungen während der Abfahrt beim Üben einer neuen Fahrtechnik eingesetzt.

Diese Dissertation hat erstmalig untersucht, welche taktilen Reize mit Körperbewegungen assoziiert werden und welche Reize als Bewegungsanweisungen verwendet werden können. Die gewonnenen Erkenntnisse über die Wahrnehmung und Interpretation der untersuchten Reize haben zu einem Leitfaden für den Entwurf von taktilen Bewegungsanweisungen geführt. Diese Forschungsergebnisse können auch in anderen Domänen angewendet werden, in denen unmittelbare Rückmeldung zu Fehlhaltungen während der Ausübung physischer Aktivitäten nicht dargeboten werden kann. Zum Beispiel könnten taktile Bewegungsanweisungen helfen, Verletzungen in unbeaufsichtigten Situationen im Alltag vorzubeugen. Außerdem könnten sie auch in der Rehabilitation für die Wiedererlangung von motorischen Fähigkeiten eingesetzt werden.

In dieser Arbeit wird auch ein tragbares System vorgestellt, das es erlaubt, einfache Körperbewegungen zu messen und künstliche taktile Reize am Körper zu generieren. Dieses System diente als Grundlage für die Entwicklung der taktilen Bewegungsanweisungen und deren Untersuchung in realen Bedingungen. Basierend darauf wurde als Beispiel der erste tragbare Assistent für Snowboardtraining entwickelt, der während der Abfahrt bestimmte Bewegungen des Fahrers messen, interpretieren, und taktile Bewegungsanweisungen als Rückmeldung geben kann.

Acknowledgements

First, I thank my advisor, Jan Borchers, who gave me the time, freedom, guidance, and \$\$\$ that I needed to find, work on, and finish my thesis. I really enjoyed the pleasant atmosphere from my first day to the last day at his chair. I will miss this for sure.

I also thank my co-advisor, Martina Zieffle, who is one of my first and most preferred professors whom I have met.

Rafael “Tico” Ballagas and Eric Lee receive my full admiration. I really appreciate them as first colleagues from whom I have learned so much as freshman PhD student. Although I am a little bit older, both were, and still are, one step ahead of me.

A very special thanks goes to David Holman. He inspired me to find a research topic that had to do with what I like to do: “Then do something with snowboarding!”. Perhaps, I should not have listened to him. By now, snowboarding reminds me of work. It used to be holiday.

Many, many thanks go to all students who did the hard work for me (tee-hee): my diploma thesis students Christian Guggenmos, Adalbert Schanowski, Markus Jonas, Mareike Jacobs, and Anke Hilgers; and my student assistants “Frank” Xiaojun Ying and Sören Busch. I also thank Jan Benzenberg for his electrotechnical support.

Moreover, I thank Mirko Romstadt and Emanuel Angelescu from RWTH’s Snow Sport Team, who assisted me during user studies on the slope, and Jeroen Heutz and Martin Winkelmann from SnowWorld Landgraaf, who generously supported these field studies.

I want to acknowledge three colleagues in particular: Thorsten Karrer, who always had the time to answer my silly questions; and Jonathan Diehl, Chatchawan Wacharamanotham, and Thorsten Karrer, who reviewed this monograph.

I’m glad to have met many students and staff who also joined the Media Computing Group (roughly in order of appearance): Britta Grünberg, Marius Wolf, Eugen Yu, Yvonne Jansen, Ingo Grill, Nils Beck, Mahsa Jenabi, René Reiners, Anna Koster, Clarissa de Gavarelli, Alex Hoffmann, Julie Wagner, Tim Hemig, Elaine Huang, Gero Herkenrath, Malte Weiß, Sarah Mennicken, Max Möllers, Florian Heller, Moritz Wittenhagen, Leonhard Lichtschlag, and the unnamed as well!

Finally, I thank my parents for their continuous love and support.

Conventions

We will use the following conventions throughout this thesis:

We will use the plural “we” instead of the singular “I”, even when referring to work that was primarily or solely done by “the author”.

Technical terms or jargon that appear for the first time are in *italics*.

Some of the material covered in this thesis has been previously published at conferences. We will note these parts in the corresponding text passages.

Chapter 1

Introduction

“Defer no time, delays have dangerous ends;”

—*William Shakespeare (excerpt from Henry VI)*

Sports scientists have shown that frequent feedback on an athlete’s performance and concurrent feedback provided during the execution of body movements can improve the performance and learning of motor skills [Wulf, 2007]. In general, coaches provide feedback via three channels: they explain and demonstrate exercises, and they move the athlete’s body into correct position. Even so, the type and the frequency of feedback that athletes receive during training depend on the sport. Compare, for example, typical lessons in the tennis court to lessons on the slope (see Figure 1.1):

Frequent feedback supports learning of motor skills.

As a tennis student, you learn how to perform backhand and forehand strokes. Your instructor explains how to position your body and how to wield the racket. He talks to you whenever you need assistance. Moreover, he guides your arm when your technique is wrong.

Tennis scenario: frequent feedback during exercises

As a snowboard student, you learn how to perform turns. Your instructor explains how to move your body during the ride. Then, he descends the slope to demonstrate correct technique. As he stops, you start to slowly descend. You are afraid to fall while turning the board. You look at your feet and focus on keeping balance. The snowboard unexpectedly accelerates. You lose control and... ouch! Your instructor cannot tell you how to adjust posture to avoid further falls; he is too far away. He cannot push you into correct position either. You only receive delayed feedback on your riding mistakes, after descending the slope.

Snowboarding scenario: limited and delayed feedback

Spoken instructions played back over earplugs could assist students who are spatially separated from their coaches. Such messages, however, are less appropriate in noisy environments because they can block important audio cues that occur naturally. In our example, the sound of the snowboard shoving snow away helps the rider to adjust the pressure and the edging angle. Without these audio cues, the rider’s performance would degrade.

Spoken instructions are often unsuitable in noisy environments.



Figure 1.1: Left: Tennis students frequently receive spoken, visual, and tactile feedback during exercises, which helps them to differentiate between correct and wrong movements (courtesy of [Cooper Aerobics Center, 2010]). Right: Snowboard students do not receive feedback from their instructor during exercises. They only receive instructions before descending the slope and feedback after the run.

Moreover, the sound stemming from other skiers and snowboarders who quickly approach from behind can help prevent accidents.

1.1 Tactile Instructions Correct Wrong Posture

Tactile instructions signal how to move the body during physical activities.

Instead of spoken instructions played back over earplugs, small vibration motors attached to the body could generate artificial tactile stimuli that instruct athletes how to correct their posture. These stimuli would not interfere with environmental audio cues. Moreover, they would directly stimulate the skin such that athletes could immediately feel which part of the body to move, as if the coach pushed or pulled their limbs into the correct position. All physical activities and sports where coaches cannot provide feedback during exercises could benefit from such *tactile instructions*, including skiing, surfing, dancing, and martial arts. This idea has been mentioned before [Nakamura et al., 2005, Van Erp et al., 2006, Lieberman and Breazeal, 2007], but it has not yet been explored in detail.

Wearable automatic sensing and feedback devices

Our vision relates to *wearable computing*, which inspired researchers since the 1960s: “Wearable computing pursues an interface ideal of a continuously worn, intelligent assistant that augments memory, intellect, creativity, communication, and physical senses and abilities.” [Starner, 2001]. We imagine wearable computers and *smart clothes* [Mann, 1996] that supervise body movements and that automatically provide tactile instructions when the athlete’s posture is incorrect. Such systems have to accomplish three tasks:

1. Sense the athlete's posture and body movements with sensors inserted into the clothes and the sports equipment.
2. Build a posture and motion model of the body and determine if the athlete's movements are correct.
3. If the athlete's posture or movements are incorrect, provide tactile instructions to those parts of the body that have to be adjusted.

Assume again you were trying to perform consecutive turns on a ski run. This time, however, your ski suit and your snowboard have built-in sensors. Moreover, your suit contains vibration motors that are located at the thighs and at the torso. While descending the slope, focusing on keeping balance, you do not notice that you unconsciously shift your weight towards the right foot, which points backwards on the snowboard. This posture makes you feel safer because you do not lean your upper body downwards towards the slope. Riding with this weight distribution, however, makes it difficult to perform turns. Suddenly, you notice a push laterally at your upper right thigh and right shoulder as if your instructor pushed you towards the left. The vibration motors signal to shift your weight to the left foot towards the front of the snowboard, thereby leading to a safe turn.

Future snowboarding scenario: tactile instructions during descents

As envisioned in this scenario, learning to snowboard could become similar to learning to play tennis where the coach can directly guide the athlete's body into correct position. In particular, wearable sensing and feedback devices that automatically provide tactile instructions during exercises could enhance the learning experience in all sports where athletes do not receive immediate feedback on their performance because they are spatially separated from their coach. These devices could also support coaches who cannot focus their attention on all athletes at the same time during courses.

Automatic instructions support athletes during training and coaches while teaching.

1.2 Context and Scope of this Thesis

Sport technologies are one thriving application domain for pervasive and wearable computing [Chi et al., 2005]. Researchers from various fields, including sport, kinesiology, physiology, and computer science, have started to develop systems for measuring muscle movements and other physiological aspects that can help coaches understand and improve the performance of athletes, for example while swimming and rowing [James et al., 2004], or while skiing [Michahelles and Schiele, 2005, Brodie et al., 2008]. As Chi et al. [2005] stated, "Almost any sport could benefit from equipment enhancements as well as novel measurement and analysis of athletes' performance.". In fact, several systems that can provide visual, audio, or tactile feedback during training have already been presented. Some systems target at elite athletes, whereas others focus on amateur athletes. Some systems are research prototypes, whereas others can be purchased. In this section, we will give an overview of these systems and of their most popular application domains, including sports training and daily physical activities.

Wearable technology can help athletes to improve their performance.

1.2.1 Visual and Audio Feedback

Rapid visual and audio feedback for elite athletes

Baca and Kornfeind [2006] introduced rapid feedback systems for rowing, table tennis, and shooting, which visualize on computer displays the quality of an athlete's technique, based on sensors built into the sports equipment. Another example is the *interactive throwing sleeve*, which is a high-tech armband with sensors at the wrist and elbow [Technology Review, 2008]. This wearable training tool for basketball players measures arm movements when the athlete shoots the ball. A remote computer analyzes the wirelessly transmitted data and maps the result to musical cues, which allow players to immediately recognize arm movements that lead to successful shots.

Personal training devices offer visual and audio feedback for amateur athletes.

Other systems target at amateur athletes and are meant to motivate fitness and a healthier lifestyle. Examples include small armband-sized weight management tools and personal training devices that can provide visual or audio feedback after workout or to specific body movements, and that can play music that suits the training program [Asselin et al., 2005, Wijnalda et al., 2005]. A popular commercial device is *GoWear fit*, which can monitor all physical activities performed during the day and which can display the burnt calories [BodyMedia, 2008]. Another commercial system is *Nike + iPod*, which can summarize the time, distance, pace, and the burnt calories while jogging [Apple, 2008].

Audio feedback for golf training

The *Sonic Golf Club* is a commercial gadget that focuses on golf training. This club measures the acceleration of golf swings with sensors inserted into the shaft and converts the measured speed to sound patterns [Sonic Golf, 2008]. Similarly, the *Suunto G6* watch has built-in sensors for analyzing certain characteristics of golf swings, such as the duration, the speed, and the length of the swing plane in degrees [Suunto, 2009]. Although these devices only address a small subset of body movements that can affect a golfer's technique, amateurs can immediately experience after putting how fast and wide they swung their club such that they can adjust their technique during practice.

Audio and visual feedback for martial arts training

Martial artists can also benefit from instant feedback on their performance. The quality of punches is often difficult to assess because the involved body movements are quickly executed. To address this issue, Takahata et al. [2004] used accelerometers to analyze the timings and the forces of the wrists, the ankles, and the waist while punching, and turned these measurements into sound patterns. This audible feedback enabled amateurs to hear and compare their movements to the instructor's movements. Also, Kwon and Gross [2005] combined accelerometers with video analysis to visualize the power of punches as circles of different sizes.

Audio feedback for ski training

A ski instructor devised a simple tool for correcting the posture of skiers. *The Ski Coach* [Braisby, 2005], a commercially available mechanical device, worn in a backpack, generates sound feedback that signals correct upper body posture during turns. This tool consists of a tube slightly curved upwards with three ball bearings (see Fig. 1.2). Skiers who correctly per-



Figure 1.2: The Ski Coach [Braisby, 2005]. The clink of balls signals that the posture of the shoulders is correct (courtesy of Chris Braisby).

form turns without tipping their shoulders hear an audible clink that the moving balls produce when the forces that develop during turns pull these balls from one end of the tube to the other end. Skiers who incorrectly tip their shoulders do not hear this clink; the forces that develop during turns are too weak to move the balls along the tube.

1.2.2 Tactile Feedback and Force Feedback

Up to now, only few systems have been devised that can provide feedback over the tactile channel, typically in the form of vibrational signals. Nakamura et al. [2005] experimented with such tactile stimuli at the wrist in order to initiate dance movements. Van Erp et al. [2006] reported that tactile stimuli have been tested as directional commands for navigation during soccer training, as corrective instructions for improving the posture of cyclists and speed skaters, and as timing signals for coordinating body movements while rowing and dancing. Lieberman and Breazeal [2007] applied tactile stimuli to the joints in order to indicate movement deviations from the target movement; these stimuli resembled a “force-field” built around the correct motion path. Moreover, Huang et al. [2010] demonstrated that passive tactile feedback can help teach motor skills for playing the piano.

A few systems focused on clinical applications. Wall et al. [2001] built a balance prosthesis that delivered tactile stimuli to the shoulders and laterally to the torso for reducing postural sway. Priplata et al. [2003] suggested vibrating insoles for helping elderly people to maintain their balance while standing still. Also, Lindeman et al. [2006a] proposed tactile stimuli to warn patients of improper joint movements, such as after surgery.

Besides tactile feedback, haptic devices that stimulate the sense of touch through force feedback [Oakley et al., 2000] have been developed to teach motor skills. For example, a haptic interface can assist stroke patients in moving their arms along a predefined path through forces that pull wrong

Tactile feedback
for sports training
and motor skill
learning

Tactile feedback
for rehabilitation

Force feedback for
rehabilitation and
motor skill
learning

movements of the limb in the correct direction [Loureiro et al., 2004]. Overall, several studies indicate that this haptic guidance can enhance rehabilitative exercises and can be used for training patients lost motor skills [Holden, 2005, Bluteau et al., 2008, Yang et al., 2008].

Tactile feedback could support patients at home and could assist people in unsupervised daily physical activities.

In our view, automatic sensing and feedback devices that provide tactile feedback could also support and motivate patients to continue practice at home, in particular in-between the short sessions with doctors. Moreover, these devices could assist in unsupervised situations during daily physical activities when people do not receive feedback on their posture and body movements. For example, many people who pick up a heavy box from the floor bend their upper body forward but keep their legs straight, which can injure the lower back and which can cause lumbago. Smart clothes that detected these harmful movements could immediately deliver tactile instructions to the thighs, thereby signaling to flex the legs.

1.2.3 Outlook

Wearable computers can break new ground in sports training.

The aforementioned examples illustrate that there is an increased interest in personal training and monitoring devices for sports, for medical applications, and for daily physical activities. On the one hand, performance statistics motivate and allow athletes and amateurs to keep track of their progress between workout sessions. On the other hand, frequent and concurrent feedback during training can improve the performance of athletes. Wearable computing can break new ground in designing technologies that sense and analyze body movements and that immediately provide feedback and instructions, either over the visual, the auditory, or the tactile channel.

In this work, we have focused on tactile feedback. This channel has not been explored yet in detail for providing realtime feedback and instructions that could signal how to adjust the posture and how to move the body during physical activities. In particular, we have investigated

- which artificial tactile stimuli delivered across the body could work as instructions that represent body movements in an intuitive way,
- how well these tactile instructions were perceived and recognized in active situations that were physically and cognitively demanding,
- how tactile instructions compared with spoken instructions delivered over earplugs in active situations, and
- if tactile instructions could enhance the performance and learning of motor skills in active situations.

1.3 Thesis Contributions

This thesis evolved out of missing realtime feedback while snowboarding. To instruct snowboarders how to correct their posture while descending the slope, we imagined a wearable system that automatically sensed the rider's movements and that provided tactile instructions to the relevant parts of the body. This initial idea resulted in the design of a general set of full-body tactile patterns that can represent body movements in an intuitive way [Spelmezan et al., 2009b]. These tactile patterns constitute a simple tactile language of motion instructions for physical activities. This language can guide through sequences of body movements similar to words that form sentences in spoken languages [Spelmezan et al., 2009a].

We have designed and evaluated a language of tactile instructions for physical activities.

Our work also addressed the three tasks that wearable sensing and feedback devices have to accomplish: sensing of posture and body movements; detecting mistakes; and providing instructions (see section 1.1). As an example for developing such a system, we have informed the design of a wearable snowboard training system [Spelmezan and Borchers, 2008], and we have built hardware and software tools that support rapid prototyping of simple wearable computing applications [Spelmezan et al., 2008]. These tools enabled us to build the first assistant for snowboard training that could sense and interpret the movements of the snowboard and the posture of the rider [Spelmezan et al., 2009c]. To evaluate the proposed approach to teaching motor skills in a real-world setting, we will report in this dissertation the results of a field study that was conducted with amateur athletes who experienced tactile instructions during a snowboarding course.

We present the first wearable snowboard training system.

The main contributions of this thesis address several research topics that relate to the interaction between humans and computers (see Fig. 1.3):

- The development of hardware and software tools for rapid prototyping of wearable computing applications that can sense posture and body movements during physical activities and that can provide artificial tactile feedback for corrections.
- The design of full-body tactile patterns that can represent body movements in an intuitive way. These patterns can be quickly learned as instructions and recalled in the long-term. Moreover, these tactile motion instructions constitute a simple language that can communicate how to move the body during physical activities.
- The evaluation of tactile motion instructions regarding their intuitiveness, learnability, perception, and recognition in active situations.
- The evaluation of tactile motion instructions for teaching motor skills during physical activities.

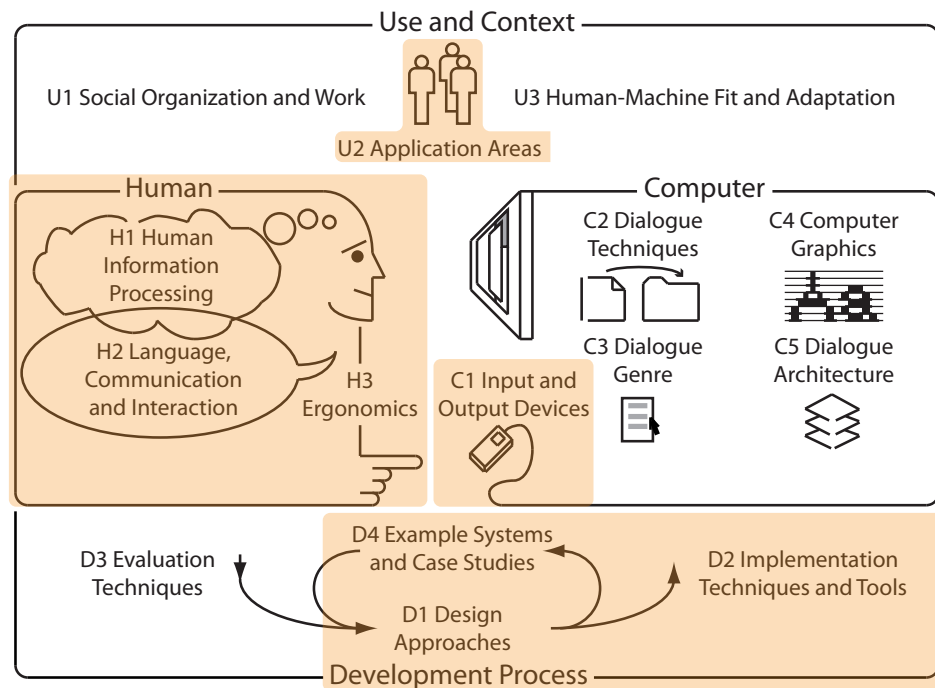


Figure 1.3: Research in Human-Computer Interaction (HCI) addresses several topics that have been outlined by the ACM SIGCHI Curricula [Hewett et al., 1992]. This thesis contributes to the highlighted areas.

1.4 Thesis Structure

This thesis is structured in four parts and includes the following chapters:

Part I: Wearable Sensing and Feedback Devices

Chapter 2 focuses on wearable computing, context recognition, and state-of-the-art wearable systems that can sense posture and body movements.

Chapter 3 describes the custom-built wearable sensing and feedback device and the developed software tools that enabled us to design and to evaluate tactile instructions with users in laboratory and in field studies.

Chapter 4 informs the design of a wearable snowboarding assistant and presents algorithms that can classify basic context information on the slope.

Part II: Tactile Motion Instructions

Chapter 5 discusses the fundamentals of tactile perception and introduces related work on tactile display technologies and their applications.

Chapter 6 addresses the design of artificial tactile stimuli that can represent body movements in an intuitive way and evaluates how young adults

perceive and interpret these stimuli in stationary and in active situations.

Chapter 7 focuses on the language aspect of tactile motion instructions and investigates how accurate young adults can recognize sequences of instructions that are based on two different encoding metaphors. This chapter also examines how intuitive users regard the designed tactile stimuli to represent body movements and how well they can remember the meaning of these stimuli after an extended time period without additional practice.

Chapter 8 describes a field study that was conducted with snowboarders to evaluate tactile motion instructions for teaching motor skills. Finally, the composed set of tactile motion instructions and recommendations for designing tactile motion instructions are presented.

Part III: Conclusion

Chapter 9 summarizes the presented work.

Chapter 10 describes future challenges.

Part IV: Appendix

The appendices of this thesis provide supporting materials:

Appendix A shows the circuit schematic of the developed motor shield.

Appendix B, **Appendix C**, and **Appendix D** comprise the post-study questionnaires for the conducted field studies.

Appendix E discusses the structure of formal languages.

Part I

Wearable Sensing and Feedback Devices

Chapter 2

Wearable Computing

“Where a calculator on the ENIAC is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may have only 1,000 vacuum tubes and perhaps weigh 1.5 tons.”

—Unknown, *Popular Mechanics*, March 1949

In this dissertation, we have investigated artificial tactile stimuli as instructions how to move the body during physical activities. To design these instructions necessitated a wearable feedback system that controlled actuators for generating tactile stimuli on the skin. To evaluate these instructions in real-world conditions necessitated a context-aware wearable system that sensed and analyzed body movements, and that automatically provided instructions on incorrect posture. In this chapter, we will introduce the concept of wearable computers, and we will present technologies for building wearable sensing and feedback devices, as envisioned in section 1.1.

2.1 Wearable Computers

Wearable computers have a wide range of applications. Several systems have been presented and have been deployed in particular in health related domains. These systems can continuously record and supervise a patient’s vital signs, physical activities, or exercises; they can inform patients on their current medical status; and they can automatically notify physicians of emergencies [Martin et al., 2000, Steele et al., 2003, Pentland, 2004, Lukowicz et al., 2004, Jovanov et al., 2005, Sung et al., 2005]. Some devices were designed for monitoring gait [Paradiso et al., 2004] or sway [Brunelli et al., 2006]; these devices provided audio feedback for corrections.

Wearable
applications for
health related
domains

Besides assisting coaches in analyzing the performance of athletes and in motivating amateurs to reach fitness goals (see section 1.2), wearable systems have been built that can support referees in scoring sparring matches [Chi et al., 2004] and snowboarding competitions [Harding et al., 2009].

Wearable
applications for
sports
competitions

Wearable applications for industrial settings

Wearable devices have also been deployed in industrial settings [Stanford, 2002]. Due to their small size, they can support trainees and workers in their natural work environments, for example while assembling and maintaining complex systems like cars and airplanes, or they can assist rescue workers in emergency situations [Lukowicz et al., 2007].

A wearable computer is not just a device worn on the body.

The aforementioned examples illustrate that wearable computers become increasingly important as assistive technologies. But what is a wearable computer? The adjective “wearable” implies that the computer is small and portable enough to be worn or carried on one’s body [NOAD2, 2005]. This straightforward definition only addresses the physical size of the device. Wearable computers, however, have specific characteristics that differentiate them from desktop computers and personal digital assistants. Rhodes [1997] has first outlined these characteristics: besides being portable, always on, and designed for hands-free use, they sense and exploit the physical context and proactively convey relevant information to the user.

Wearable computers are aware of the context in which they are used.

Later works referred to these characteristics and refined the concept of wearable computing. For example, Dey et al. [1999] highlighted *context-awareness* and *proactivity*: being “proactive” is “the essence of context-aware computing: the computer analyzes the user’s context and makes task-relevant information and services available to the user, interrupting the user when appropriate”. Starner [2001] described the ideal attributes of wearable devices: they observe and model the user’s environment, the user’s physical and mental state, and its own internal state; they support input and output modalities that best fit to the user’s context and provide *context-sensitive* reminders as appropriate.

The user can simultaneously interact both with the wearable device and with the environment.

Lukowicz et al. [2004] defined wearable systems as “mobile electronic devices that can be unobtrusively embedded in the user’s outfit as part of the clothing or an accessory”. Such systems are context-sensitive because they “model and recognize user activity, state, and the surrounding situation”. Moreover, wearable computing offers a new interaction concept between user, system, and environment: the user simultaneously interacts both with the environment and with the system, while the system directly interacts with the environment and further mediates the interaction between the user and the environment. This concept is fundamentally different to the interaction in conventional mobile systems, which forces users to focus on the interface and to interact either with the system or with the environment, but not with both at the same time.

2.2 Context-Awareness

As noted above, context-awareness is fundamental to wearable computing. *Context* is an umbrella term for information that can describe the situation of an object, a place, or a person relevant to the interaction between a user and an application [Dey, 2001]. Context includes environmental conditions, the state of surrounding objects, the user’s location, and human activities

[Rhodes, 1997, Schmidt et al., 1999, Dourish, 2004, Lukowicz et al., 2004]. Context-aware systems use sensors that measure certain signals and physical conditions that can yield this information.

Recognizing context from sensor data is similar to recognizing speech from different speakers [Intille et al., 2004]. Speech is one specific form of sensor data that is noisy, ambiguous, and that often considerably varies between users. The goal is to map this variable data into distinct classes based on the characteristics of the speech. To capture the variability in speech, machine learning techniques such as Hidden Markov Models [Rabiner, 1989] are used for building statistical and computational models based on previously annotated training data sets. The new speech that has to be recognized is then compared to these models and mapped to the class that best describes the speech's characteristics.

Context recognition is a classification problem that resembles speech recognition.

Of particular interest to context-aware wearable applications is the recognition of the user's activity, gestures, body movements, and posture:

Activity recognition addresses the physical activities that people perform during the day, such as walking, running, bicycling, standing still, climbing stairs, riding an elevator, watching TV, cooking, or brushing teeth [Bao and Intille, 2004]. The motion patterns of the body can reveal these activities. To measure these patterns, wearable systems typically use accelerometers to sense acceleration at various body locations. Based on the measured acceleration patterns, the system identifies what the user does.

Activity recognition

Gesture recognition addresses movements that are often performed with the hands or with the arms. Such gestures can be captured with *inertial measurement units* that comprise accelerometers for sensing translation and acceleration in three dimensions, and gyroscopes for sensing rotation [Benbasat and Paradiso, 2002]. Gestures become increasingly important in mobile and wearable computing applications because they can enable "eyes-free" control and interaction with devices [Brewster et al., 2003].

Gesture recognition

Motion recognition focuses on fluid and continuous movements of the whole body. Similar to gestures, the translation and the rotation of the body and its limbs are sensed in three dimensions. Depending on the application scenario, various technologies are combined [Welch and Foxlin, 2002]. These technologies include inertial measurement units [Kunze et al., 2006], video analysis and accelerometers [Kwon and Gross, 2005], or inertial measurement units and ultrasonic sensors [Vlasic et al., 2007].

Motion recognition

Posture recognition refers to the static pose of people. Stretch and bend sensors woven into clothes can yield the position of the trunk and the limbs, such as whether the torso is bent forward or rotated to the side, or whether the arms are stretched or flexed [Farrington et al., 1999, Mattmann et al., 2007]. Threshold tests on the orientation of accelerometer data often suffice to detect transitions among simple postures, such as sitting, standing, or lying [Farrington et al., 1999]. To recognize postures that are more complex or detailed, machine learning technique are applied [Mattmann et al., 2007].

Posture recognition



Figure 2.1: MTx orientation tracker and MVN motion capture suit with 17 MTx units (courtesy of [Xsens Technologies B.V., 2010]).

2.3 Toolkits for Building Wearable Computing Applications

Wearable sensing
and feedback
devices

The wearable sensing and feedback devices that we have proposed for providing tactile instructions during physical activities (see section 1.1) are one example of context-aware systems that would observe the user's physical state to provide context-sensitive reminders as appropriate [Starner, 2001] (see section 2.1). These devices have to accomplish three tasks: the first task involves sensing of posture and body movements; the second task involves building a posture and motion model of the body such that incorrect posture and movements can be detected; the third task involves feedback for corrections, in our case, as tactile instructions applied across the body. These three tasks necessitate devices that can sense posture and body movements, software algorithms that can analyze sensor measurements and that can interpret the classified posture and body movements in realtime, and devices that can artificially stimulate the skin. In this section, we will introduce state-of-the-art sensing devices, prototyping platforms, feedback devices, and software toolkits for building such systems.

2.3.1 Sensing Devices and Prototyping Platforms

Sensing devices

Various *sensing devices* have been developed that can sense context information regarding the user's activity, posture, and body movements. Some devices are commercially available, whereas others are research platforms that cannot be purchased. These devices typically log sensor data for off-line processing, or they transmit the measurements to desktop computers or to mobile computing devices that can process this data in realtime.

MTx motion
tracker

The MTx motion tracker is a commercial sensing device [Xsens Technologies B.V., 2010]. This inertial measurement unit has gyroscopes, accelerometers,

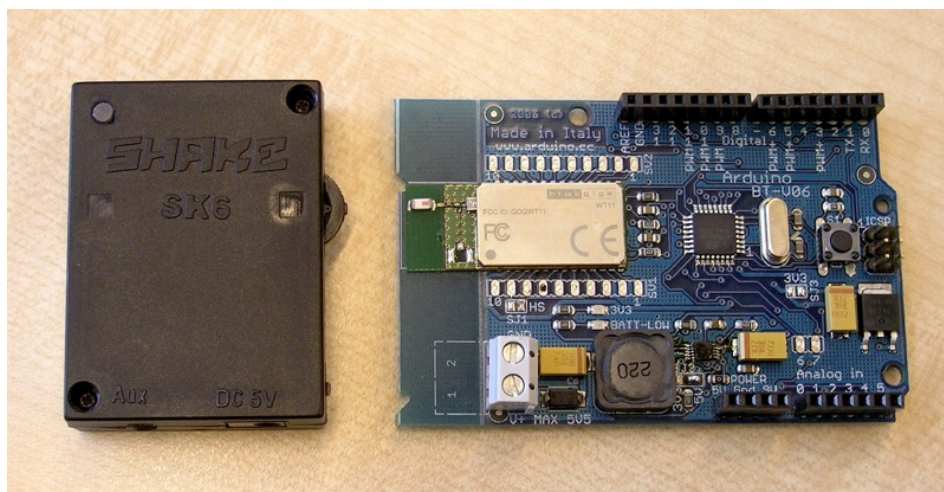


Figure 2.2: Left: The Shake SK6 sensing unit. Right: The Arduino BT prototyping platform hosts an ATmega168 8-bit micro-controller [Atmel Corporation, 2009] and a Bluetooth module for wireless communication.

and magnetometers for measuring the orientation of body segments. Several units can be combined to a motion capture suit (see Fig. 2.1). Sensor data is transmitted over Bluetooth or over a wired connection to the host computer. Previous versions of these trackers have been used for capturing body movements in martial arts [Kunze et al., 2006] and in skiing [Brodie et al., 2008], or for tracking hand gestures [Zinnen and Schiele, 2008].

Similar sensing devices are Flock of Birds [Ascension Technology Corporation, 2008] and GS-190-M [Animazoo, 2004]. ShapeWrap III [Measurand Inc., 2010] uses shape sensors made of optical fibers. Since these systems are expensive, some researchers have built similar devices from inexpensive off-the-shelf components [Aylward and Paradiso, 2006, Pirkel et al., 2008].

The Shake SK6 and SK7 [SAMH Engineering Services, 2010] (see Fig. 2.2, left) are wireless sensing devices that can transmit and receive data over Bluetooth. These matchbox-sized units have various built-in sensors, including accelerometers, magnetometers, and gyroscopes, and a plug for two external sensors. A sensor fusion algorithm calculates the compass heading in degrees relative to the earth's magnetic north pole. Moreover, these Shake devices have a built-in vibration motor and a plug for two external actuators that can generate tactile feedback. These units have been used for augmenting mobile devices with additional sensing and feedback capabilities [Williamson et al., 2007, Hoggan et al., 2009].

In contrast to commercially available sensing devices, many research platforms mainly focus on monitoring of daily activities and on activity recognition. These devices were designed to meet certain requirements, such as small size and day-long operation. For example, BodyANT [Kusserow et al., 2009] has one 3D accelerometer and can continuously sense and wirelessly stream data up to five days. Similar wireless sensing devices are WearNET

Other sensing devices for capturing posture and body movements

Shake SK6 inertial sensing unit

Research platforms for monitoring and activity recognition

[Lukowicz et al., 2002], PadNET [Junker et al., 2003], MIThril [DeVaul et al., 2003], Smart-its [Beigl and Gellersen, 2003], MITes [Tapia et al., 2006], B-Pack [Ohmura et al., 2006], and MSP [Choudhury et al., 2008]. Some of these systems are modular and connect with prototyping shields or daughter boards, including the Hoarder board [Gerasimov, 2002], PadNET [Junker et al., 2003], Smart-its [Beigl and Gellersen, 2003], MIThril [DeVaul et al., 2003], BTnode [Beutel et al., 2004], and Telos [Polastre et al., 2005].

Limitations of
off-the-shelf
sensing devices
and of research
platforms

Although off-the-shelf sensing devices are appropriate for many application scenarios, their disadvantage is that they only have a fixed set of built-in sensors that cannot be exchanged. Moreover, they typically cannot be programmed to run custom algorithms and applications that analyze sensor data in realtime. Many of the aforementioned research platforms can be customized, but they target at professionals who have knowledge in micro-controller programming and in designing printed circuit boards.

Prototyping
platforms

Another class of devices are *prototyping platforms*. They are similar to the aforementioned research platforms, but they were designed to foster rapid prototyping of applications. These platforms do not have built-in sensors, but they offer input pins to connect sensors. Some platforms also offer output pins for actuators. Moreover, many prototyping platforms can be easily programmed to analyze sensor measurements in realtime. For these reasons, prototyping platforms are often used for building custom sensing and feedback devices that address specific needs.

Toolkits for
building physical
user interfaces

Prototyping platforms that are commercially available were designed to support nonprofessionals in designing interactive systems and physical user interfaces. These platforms include Make Controller Kit [Makingthings, 2010], Phidgets [Greenberg and Fitchett, 2001], and I-CubeX [Infusion Systems, 2007]. They can connect to various sensors and actuators but normally require an external power supply and a serial connection to a desktop computer that can process sensor data. Thus, they are less suited as wearable stand-alone units for analyzing sensor measurements in realtime.

The Arduino
physical
computing
platform

Arduino [Banzi et al., 2005] is an open-source electronics prototyping platform for rapid prototyping of interactive systems and wearable applications. Arduino also functions as stand-alone unit and supports wireless data transfer, such as over Bluetooth (see Fig. 2.2, right). LilyPad Arduino is a small variant of this board. Designed to introduce novices to electronics, computing, and design [Buechley et al., 2008], this construction kit targets at wearable computing and computational electronic textiles [Buechley, 2006]. All Arduino platforms can be programmed in a C-like language.

Sun SPOT for
embedded
electronic devices

Sun SPOT [Sun Microsystems, 2004] is both a sensing device and a prototyping platform. This device was designed to support rapid prototyping of embedded electronic devices that can sense and respond to their environment. SPOTs can be programmed in Java [Sun Microsystems, 1995], and they can analyze sensor data in realtime. They function as stand-alone units, and they can form a wireless sensor network.

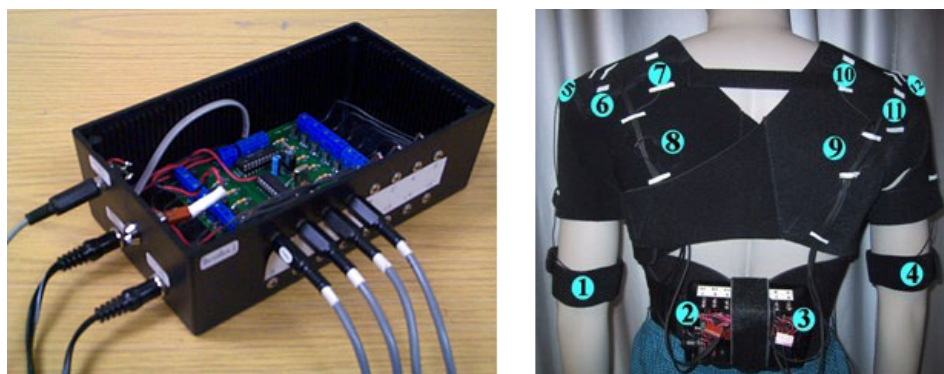


Figure 2.3: The TactaBoard [Lindeman and Cutler, 2003] controlled the TactaVest [Lindeman et al., 2004a] (courtesy of Robert W. Lindeman).

2.3.2 Software Toolkits for Sensor Data Analysis

Software toolkits focus on visualizing sensor data and on context recognition. For example, IU SENSE is a desktop application that graphically displays accelerometer data [Caracas et al., 2003]. The Georgia Tech Gesture Toolkit (GT²k) focuses on implementing gesture-based recognition systems based on Hidden Markov Models [Westeyn et al., 2003]. The Context Recognition Network (CRN) Toolbox targets at distributed activity and context recognition systems on mobile and wearable devices that run POSIX operating systems [Bannach et al., 2008]. The WUI-Toolkit focuses on designing and implementing wearable user interfaces, such as those displayed in head-mounted displays [Witt et al., 2007].

Sensor data
analysis and
context
recognition

A few other toolkits specifically support iterative and rapid prototyping of sensor-based interactions or of context-aware applications. The Context Toolkit [Dey et al., 2001] and iCap [Dey et al., 2006] target at ubiquitous computing environments. d.tools [Hartmann et al., 2006] focuses on physical user interfaces for information appliances. Exemplar [Hartmann et al., 2007] resembles IU SENSE but enables interaction design through programming by demonstration. iStuff Mobile [Ballagas et al., 2007] aims at sensor-enhanced mobile devices for ubiquitous computing scenarios [Ballagas, 2007]. These toolkits, however, are less suited for developing wearable applications and for conducting field experiments with wearable systems, as required in this work.

Sensor-based
interactions with
mobile devices
and in ubiquitous
computing
environments

2.3.3 Tactile Feedback Devices

Only few devices that are commercially available can drive actuators. The Shake SK6 (see Fig. 2.2, left) has a built-in actuator and a plug for two external actuators. Another system is the Tactor Eval 2.0 module (9 cm × 9.5 cm), which controls up to eight C2 tactors [Engineering Acoustics Inc., 2010]. Eight modules can form a master-slave setup to control 64 tactors.

Commercial
actuator systems
for wearable
computing

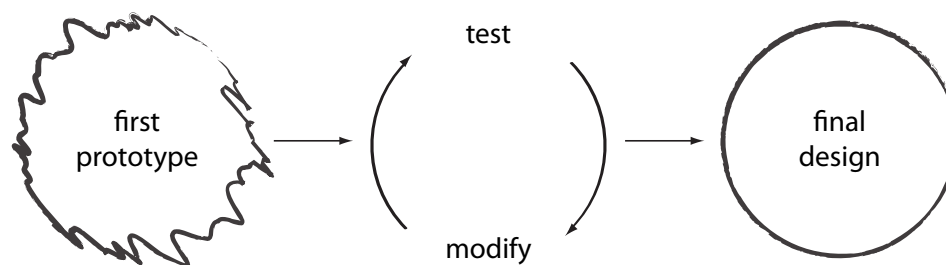


Figure 2.4: Iterative design involves several cycles where initially rough prototypes are tested with users and refined based on the gained results.

Custom-built
actuator systems

Many tactile feedback devices that can be worn on the body are custom-built prototypes for research projects [Cardin et al., 2006a,b, Jones et al., 2006]. Lindeman et al. [2006b] presented several systems. The TactaBoard (19 cm × 11 cm × 5.8 cm) (see Fig. 2.3) controlled 16 actuators and varied the intensity of the generated stimuli by *pulse width modulation* [Barr, 2001]. This board communicated to its host computer over a wired connection [Lindeman and Cutler, 2003]. The TactaBox (15.2 cm × 10.1 cm × 5.1 cm) improved the TactaBoard and supported Bluetooth communication [Lindeman et al., 2004b]. The TactaPack (5.8 cm × 3.5 cm × 1.35 cm) consisted of one built-in vibration motor and one 3D accelerometer [Lindeman et al., 2006a]. This unit was an example of a simple wireless sensing and feedback device that could sense and stream to a host computer the position of limbs during physical therapy exercises, and that could provide a tactile warning signal when the measured accelerometer signals exceeded a predefined threshold value, which corresponded to wrong limb movements.

Tactile vests for
full-body tactile
feedback

Besides these wearable motor controllers, several researchers have built tactile vests for investigating full-body tactile feedback [Yano et al., 1998, Rupert, 2000, Gemperle et al., 2001, van Erp and van Veen, 2003, Jones et al., 2004, Lindeman et al., 2004a]. These vests contained custom-built motor controllers that communicated with their host devices over Bluetooth or over a serial connection, such as the TactaVest (see Fig. 2.3).

2.4 Iterative Design: A Challenge in Designing Wearable Computing Applications

Iterative design
and prototyping
lead to usable
systems.

Iterative design and *prototyping* are key principles for designing usable user interfaces [Buxton and Sniderman, 1980, Gould and Lewis, 1985, Baecker et al., 1995, Schrage, 1996]. Although developers usually have a good idea of the final product, at the beginning of the design process they cannot foresee unexpected problems and usability breakdowns that users might face. Frequent tests of prototypes with users and redesigns of these prototypes in each iteration based on the gained insights help developers to refine initial ideas and contribute to the final design of the system (see Fig. 2.4).

These principles are of particular importance to wearable computing. Depending on the application domain and the services to provide, wearable systems have to balance various technical, economical, and social constraints and requirements, including size, weight, power consumption, processing requirements, reliability, maintenance, costs, privacy, and comfort [Schmidt and Laerhoven, 2001, Starner, 2001]. For example, users usually do not accept and wear devices that are uncomfortable or that interfere with fluid human movement [Gemperle et al., 1998, Dunne and Smyth, 2007]. To address these issues, developers of wearable systems should adopt an iterative design approach, and they should involve users in the design process as highlighted by Bass et al. [1997] and Smailagic and Siewiorek [1999].

Challenges, requirements, and constraints of wearable systems

Iterative design and prototyping, however, necessitate development tools that allow developers to quickly create user interfaces [Myers et al., 2000]. Even so, very few toolkits, platforms, and devices are commercially available that support rapid prototyping of wearable devices and user interfaces. Moreover, off-the-shelf components rarely meet all requirements and constraints that new usage scenarios might require. For these reasons, developers have to build specialized hardware that address their needs. Although custom designs can have benefits over using off-the-shelf components, for example, they can reduce effort, overhead, power consumption, and costs [Smailagic et al., 1997], they also can have disadvantages. In general, custom designs require technical expertise. Also, similar to many off-the-shelf components, custom-designed systems can result in specialized hardware that might not be reused in other settings than in the usage scenarios that they have been developed for. These conditions can increase the time and the effort for developing the intended system, and they can raise the threshold to iteratively build and test new prototypes.

Wearable computing lacks development toolkits for rapid prototyping.

We faced similar problems when we started this dissertation. In order to explore tactile stimuli as instructions how to move the body during physical activities, we were looking for a system that could control actuators for generating artificial tactile stimuli across the body. This system also had to sense and analyze posture and body movements such that tactile instructions could be automatically applied in a realistic scenario. As summarized in section 2.3, several commercially available devices and toolkits exist that we could have used, but they also had limitations. These devices could not be customized with additional sensors that were required for sensing posture and body movements in our envisioned application scenarios. In addition, they required us to use a platform for sensing context information and a different platform for providing tactile feedback.

In our case, off-the-shelf sensing and feedback devices were inappropriate for building a wearable sensing and feedback device for exploring tactile instructions.

For these reasons, we have built a general-purpose sensing and feedback device that offered connections for sensors and for actuators, based on the Arduino BT prototyping platform. Also, we have developed software that supported us in visualizing and analyzing sensor data for sensing posture and body movements. These tools enabled us to prototype simple wearable computing applications and to iteratively design and evaluate tactile instructions with users. We will describe these tools in the next chapter.

We have built custom hardware and software for rapid prototyping of wearable applications.

2.5 Closing Remarks

Building wearable applications is challenging.

The goal of this dissertation was to explore artificial tactile stimuli as instructions for correcting wrong posture and movements during physical activities. To design and evaluate tactile instructions necessitated a wearable system that sensed and analyzed posture and body movements, and that automatically provided these instructions in realtime.

Existing technologies are not versatile enough.

As discussed in this chapter, developing such a system is challenging because wearable systems have to balance various constraints and requirements. Although several off-the-shelf hardware and software tools are available for prototyping wearable computing applications, these tools have certain limitations. Sensing devices that can track body movements rely on additional computing devices for analyzing sensor measurements in realtime. Also, they have a fixed set of built-in sensors, and they do not support experiments with alternative sensors that might be required in some application scenarios. Moreover, most devices that can generate tactile feedback are research platforms that cannot be purchased, whereas off-the-shelf devices that can sense context information and that can provide tactile feedback only connect to a few external sensors and actuators. Another limitation is that software toolkits that address context recognition and sensor-based interactions either do not aim at wearable computing, or they only run on dedicated mobile devices.

In the next chapter, we will present our work on a general-purpose wearable system for sensing and actuation. This device allowed us to design tactile instructions and to evaluate these instructions with users, considering laboratory studies and field studies that also involved sensing of posture and body movements in realtime.

Chapter 3

A Wearable Sensing and Feedback System

“I must create a system, or be enslaved by another man’s.”

— *William Blake*

In the last chapter, we have summarized existing technologies for building wearable sensing and feedback devices. These technologies, however, had two disadvantages. They typically supported only a fixed set of built-in sensors, and they required two platforms: a platform for sensing and analyzing context information, and a platform for providing tactile feedback. To resolve these issues, we have developed a hardware platform that combined sensing, actuation, and wireless data transfer. Additionally, we have implemented software that assisted in analyzing sensor data and in designing tactile stimuli. These tools allowed us to prototype simple context-aware wearable applications. In particular, these tools enabled us to iteratively design and to evaluate tactile instructions with users in a realistic setting. In this chapter, we will introduce these tools, which have been presented in part in [Spelmezan et al., 2008] and in [Spelmezan et al., 2009c].

We have built tools for rapid prototyping of wearable computing applications.

3.1 Hardware Platform

Our wireless platform was intended for implementing wearable sensing and feedback devices as illustrated in section 1.1. This platform consisted of two units: a custom-built box that supported sensing and actuation (*SensAct*); and a *host device*. These units communicated over Bluetooth. Fig. 3.1 illustrates the architecture of this system and the tasks of each unit.

The wireless system consists of two units.

Both units had a programmable micro-controller that could run custom algorithms for basic signal processing and context recognition. In a typical setup, the SensAct box sampled and preprocessed sensor data, and

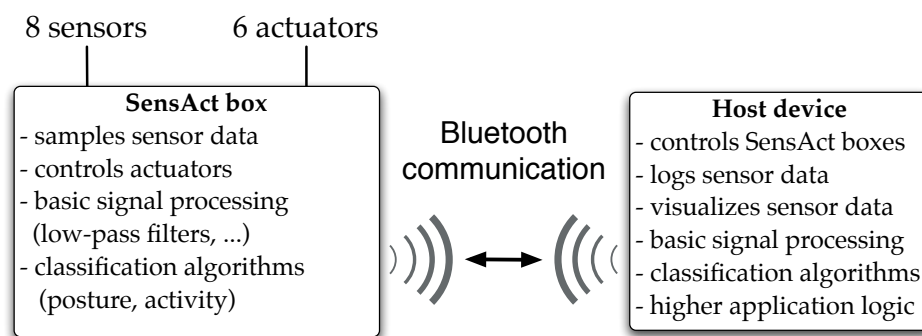


Figure 3.1: The system architecture of the wireless platform for sensing and analyzing context-information, and for providing tactile feedback.

streamed this data to the host. The host ran algorithms for context recognition and implemented higher application logic, such as rules that could interpret the classified posture. The host could also send control messages to the SensAct box. These messages could define the sampling rate for sensors, and they could start the transmission of raw sensor data or of classification results. Other control messages could activate actuators, such as vibration motors for providing tactile feedback. The SensAct box could also function as stand-alone unit that did not depend on the host to interpret context information or to control actuators.

3.1.1 The SensAct Box

The SensAct box is a general-purpose sensing and feedback device.

The SensAct box resembled the TactaBoard [Lindeman and Cutler, 2003] and the TactaBox [Lindeman et al., 2004b] (see Fig. 2.3). In contrast to these devices, the SensAct box also interfaced to sensors and offered a programmable micro-controller based on the Arduino BT (see Fig. 2.2, right). The ability to interface to different sensors and actuators and to exchange them on the fly turned this box into a general-purpose sensing and feedback device. This device was a versatile tool for conducting initial field studies that could inform the design of context-aware wearable applications.

The SensAct box was iteratively developed.

The SensAct box was developed in three iterations, as illustrated in Fig. 2.4. Each prototype was tested in a field study and improved based on the gained results (see chapter 4). The final system was used during laboratory and field studies on tactile feedback (see chapters 6, 7, and 8).

The first prototype of the sensor box

The first prototype of the SensAct box had connector sockets for six sensors but did not support actuators (see Fig. 3.2). Two AA batteries attached to the side of the box provided power for sensing and streaming of sensor data for several hours. We used this device during the first user study on the slope and logged data from various sensors for off-line analysis (see section 4.3). This box served as proof of concept for building a wearable snowboarding assistant. The hardware and the software for this box was developed by Guggenmos [2007] under the guidance of the author.

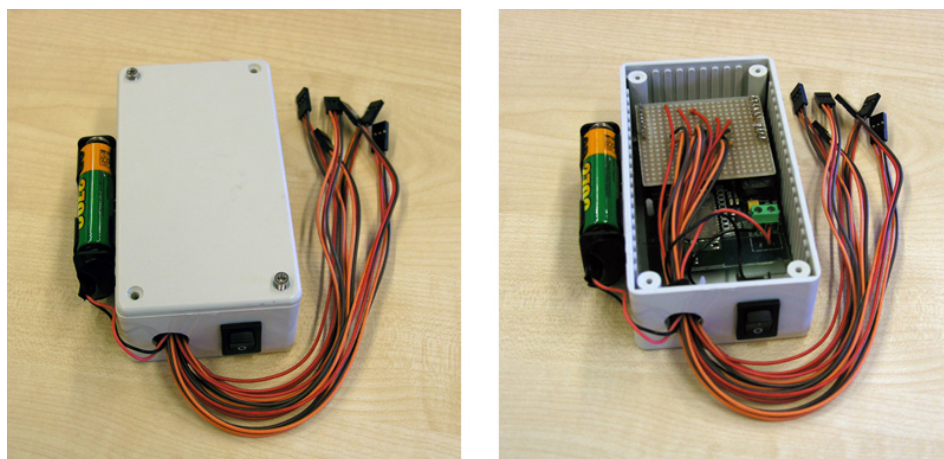


Figure 3.2: The first prototype of the SensAct box had connectors for various sensors (12 cm × 6.5 cm × 4 cm).

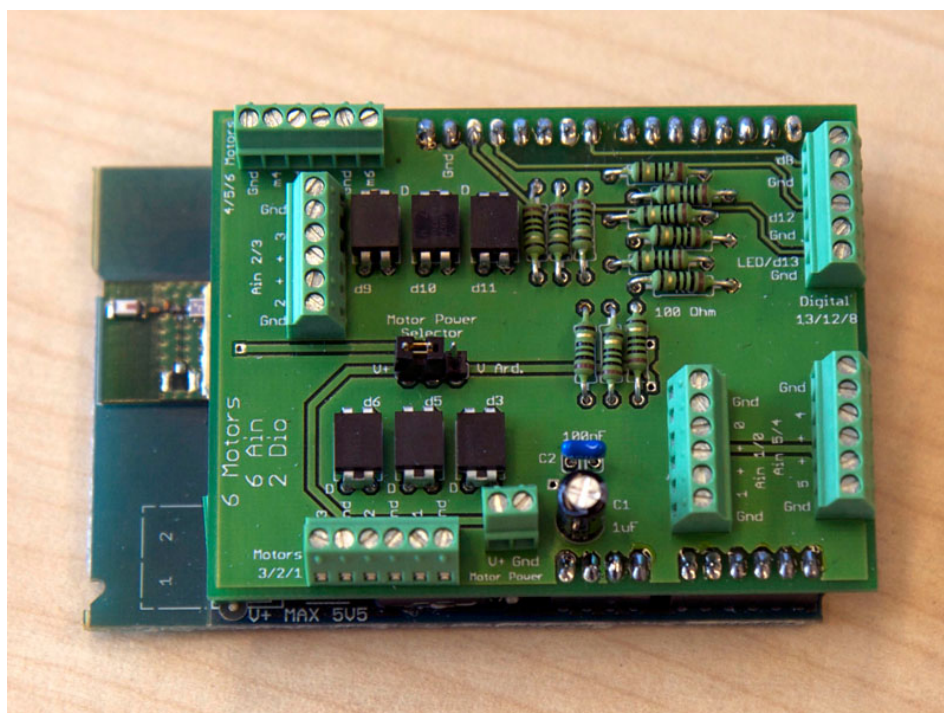


Figure 3.3: The custom-designed motor shield atop of the Arduino BT (see Appendix A for the circuit schematic).

The second prototype of the SensAct box included a custom-built motor shield (see Fig. 3.3) for the Arduino BT. This shield could control six actuators by pulse width modulation [Barr, 2001]. Actuators were connected with TS connectors and sensors with TRS connectors, which commonly served as mono and stereo audio plugs in electronic devices (see Fig. 3.4). Two AA batteries powered the Arduino BT. Four AA batteries powered the actuators. This SensAct box was developed in part by Schanowski [2008] under the guidance of the author.

A motor shield drives vibration motors for tactile feedback.

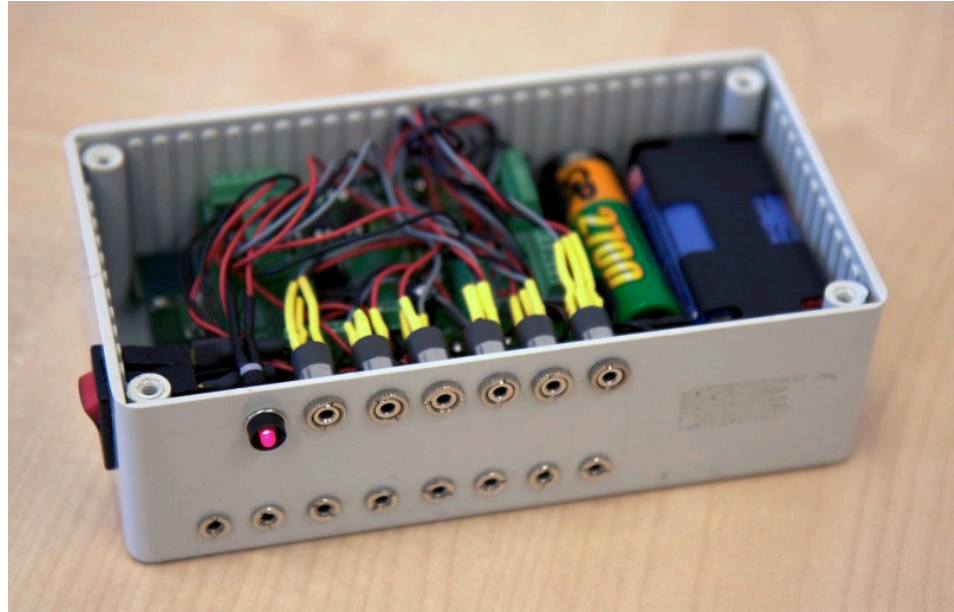


Figure 3.4: The second prototype of the SensAct box (15 cm × 8 cm × 5 cm) had TRS plugs to connect sensors (upper row) and TS plugs to connect actuators (lower row).

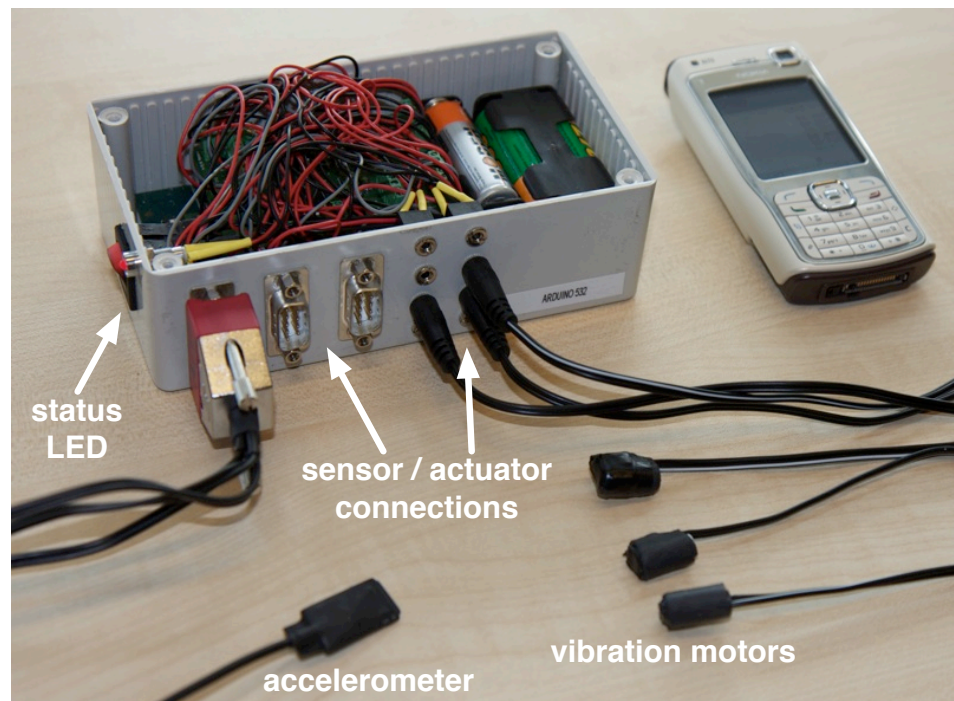


Figure 3.5: The final prototype of the SensAct box had D-sub connectors for sensors and TS plugs for actuators. A Nokia N70 mobile phone served as host device during field studies.

A user study on the slope (see section 4.4) revealed that the TRS plugs could cause loose connections, which affected the sensor measurements. Therefore, we replaced the TRS plugs with D-sub connectors for the final design of the box (see Fig. 3.5). D-sub connectors were commonly used for interfacing peripheral devices to computers. These connectors worked reliably during our subsequent field studies. In contrast to the TRS plugs, we did not experience loose connections with the TS plugs when testing actuators in the field.

3.1.2 The Mobile Host Device

The host could be any Bluetooth-enabled device. With Bluetooth, we could concurrently connect up to seven SensAct boxes for controlling up to 42 actuators. We decided for using a Nokia N70 mobile phone as host unit (see Fig. 3.5). This device could run custom-written programs in Java [Sun Microsystems, 1995] and in Python [Python Software Foundation, 1991]. In a typical setup with one SensAct box, we found no noticeable delay in the wireless communication between this host device and the box; the average time to send a six bytes command was approximately 39 ms.

A mobile phone served as host device for the SensAct box.

3.2 Software Tools

We have developed programs for our host device and desktop applications for Mac OS X that could control the SensAct box and that could visualize sensor data. Also, we have developed software libraries for implementing programs on our hardware platform. These libraries supported basic signal processing with low-pass filters and helped implementing algorithms for context recognition, which could run either on the SensAct box or on the host device. Moreover, the host device could run programs that processed raw sensor data streamed from multiple SensAct boxes.

Software libraries and tools assist in implementing wearable applications.

3.2.1 Sensor Monitor and Motor Control

Two Java programs developed for our mobile host device assisted in testing sensors and actuators during field studies (see Fig. 3.6). *Sensor Monitor* graphically displayed sensor measurements streamed from the SensAct box in realtime such that the correct placement of sensors on the body could be verified. *Motor Control* activated vibration motors such that their functioning could be tested when inserted into clothes. Both programs were programmed by Schanowski [2008] under the guidance of the author.

Field studies require frequent testing of the wearable equipment.

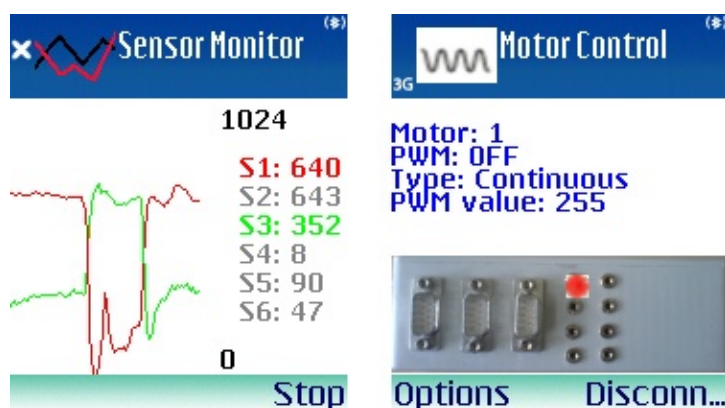


Figure 3.6: Sensor Monitor (left) and Motor Control (right) ran on the host device and assisted in testing the equipment during field studies.

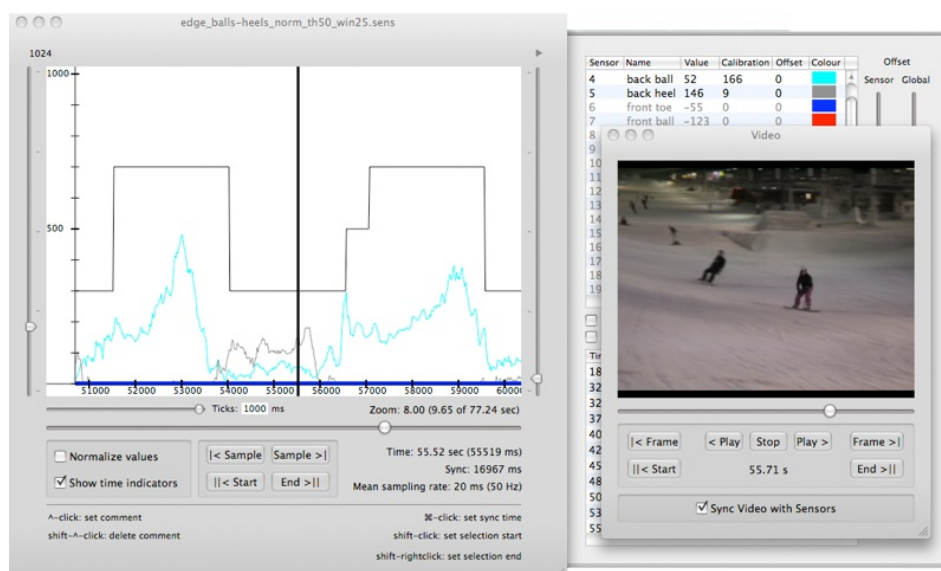


Figure 3.7: iSense supported off-line analysis of logged sensor data and synchronized this data to footage recorded during field studies.

3.2.2 iSense

iSense visualizes sensor data and video off-line.

iSense, a desktop application, visualized raw sensor measurements recorded during field studies (see Fig. 3.7). This application resembled other tools that could analyze and process sensor data in realtime, such as IU SENSE [Caracas et al., 2003] and Exemplar [Hartmann et al., 2007]. *iSense*, however, could additionally synchronize sensor data to footage such that it was possible to see how body movements affected the sensor measurements.

We have used *iSense* to analyze sensor recordings off-line.

We have used *iSense* to analyze raw sensor data recorded from snowboarders who descended a slope and to test algorithms for context recognition that could recognize a snowboarder's posture (see sections 4.3 and 4.4). To investigate tactile instructions under real-world conditions, we have ported

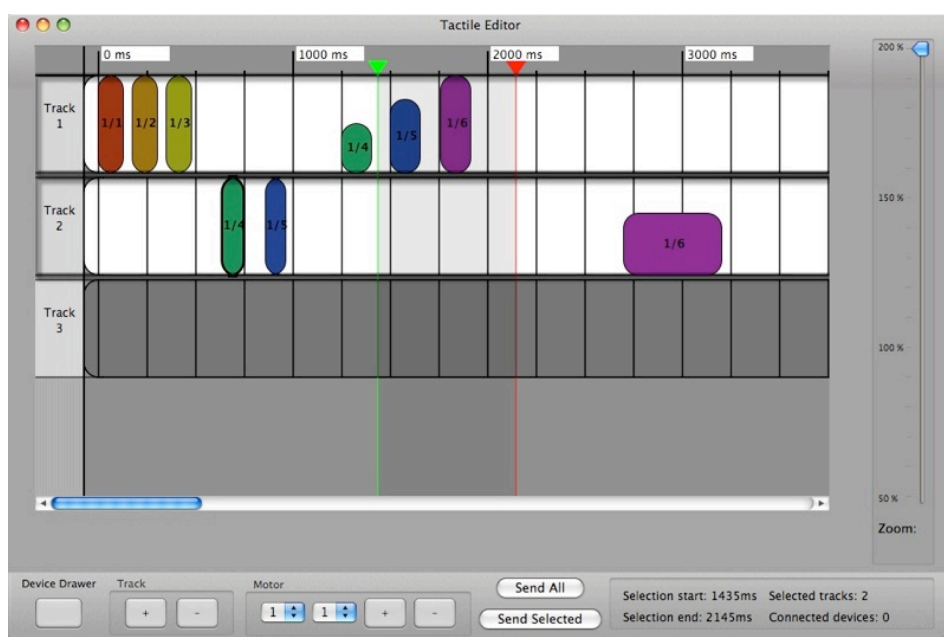


Figure 3.8: The Tactile Editor supported the design of tactile patterns by visually manipulating the properties of tactile stimuli.

these algorithms to our wearable platform, and we have implemented an interactive system that could trigger these instructions depending on the snowboarder’s weight distribution during turns (see chapter 8).

3.2.3 Tactile Editor and SensAct Control

The *Tactile Editor* evolved out of the need to design tactile stimuli that involved multiple vibration motors, such as spatiotemporal patterns (see section 5.3). These patterns could be represented as a sequence of commands that specified the order and the timing to activate individual motors. We have used a custom protocol to define these commands. For example, the following commands pulsed a single motor for 100 ms at full intensity:

```
B1;M1D1 // activate motor 1 at box 1, full intensity
B1;D100 // delay 100 ms
B1;M1D0 // deactivate motor
```

Tactile patterns that involved several motors could result in long lists of commands. To simplify the iterative design of patterns, the Tactile Editor offered a Graphical User Interface (GUI) where color-coded rectangles represented individual motors arranged on a time line (see Fig. 3.8). The height of rectangles represented the intensity of the vibration, whereas the width represented the duration of the vibration. The distance between neighboring rectangles denoted the delay between sequential stimuli. Several tactile tracks could be defined and transmitted to SensAct boxes for evaluation.

Spatiotemporal patterns involve a sequence of tactile stimuli.

Tactile Editor enables the visual design of tactile stimuli.

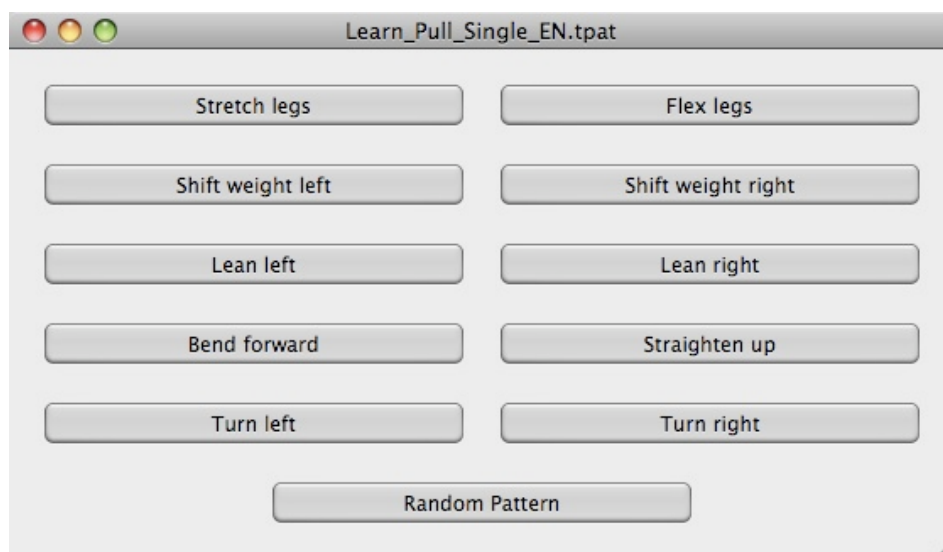


Figure 3.9: To support lab studies on tactile feedback, tactile pattern files could be loaded and displayed in a dedicated window. Each button represented a specific tactile pattern.

These command lists could also be exported to text files that were processed by the mobile host device. This application was programmed primarily by Jonas [2008] under the guidance of the author.

SensAct Control

We have additionally developed another desktop application, called *SensAct Control*. This application could process these text files and could display the names of the tactile patterns as buttons in a window (see Fig. 3.9). Pressing these buttons activated the motors on the SensAct boxes.

Designing tactile experiences becomes increasingly important across various domains.

The Tactile Editor resembled other graphical development environments for designing artificial tactile stimuli. These tools, however, were intended to support other application scenarios. Immersion Studio [Immersion Corporation, 2010a] addressed feedback effects that could be rendered by joysticks or game-pads for computer games. VibeTonz [Immersion Corporation, 2010b] focused on the design of tactile effects that could enhance applications running on mobile devices. The Haptic Editor [Enriquez and MacLean, 2003] focused on the design of haptic icons that could enrich the interaction with everyday manual controls, such as handles and joysticks (see also section 5.3). These icons were defined as waveforms, which the output device could translate into forces.

3.3 Closing Remarks

We have built tools for prototyping wearable computing applications.

In this chapter, we have described custom-built tools for prototyping wearable computing applications. We have designed these tools in order to support two goals that were relevant for this dissertation. First, we in-

tended to investigate artificial tactile stimuli as instructions how to move the body during physical activities. Second, we intended to build a wearable system for evaluating these tactile instructions in the field, based on posture and body movements that were sensed and classified in realtime. Since off-the-shelf sensing and feedback devices were less appropriate for this purpose, we have developed a wireless hardware platform for experimenting with sensors and actuators in the field. We have also implemented custom software for visualizing and analyzing sensor measurements off-line and online during field experiments.

As an example for using this platform and these tools, we will report in the next chapter how we have built the first wearable system for sensing and analyzing a snowboarder's posture and body movements during descents. This system was required for testing tactile instructions with potential users in a realistic setting. In the subsequent chapters, we will then report the user studies that we have conducted for designing tactile instructions and for evaluating these instruction in static and in active situations.

Chapter 4

Towards a Wearable Snowboarding Assistant

“Have you noticed that whatever sport you’re trying to learn, some earnest person is always telling you to keep your knees bent?”

—*Dave Barry*

The missing realtime feedback on performance while snowboarding was our initial motivation for exploring tactile stimuli as instructions how to move the body. To evaluate these instructions in the field, we decided to focus on this domain as an example. This goal required us to build a system that could automatically apply tactile instructions during a snowboarding course, depending on the rider’s movements while descending the slope.

In the last chapter, we have presented a platform for controlling vibration motors. This platform also supported sensing of posture and body movements, and enabled us to prototype simple wearable computing applications that involved sensing and actuation in realtime. In this chapter, we will describe the field studies that we have conducted with snowboarders for developing a simple wearable assistant for snowboard training.

To develop this system, we have first interviewed snowboard instructors (see section 4.1). These interviews helped us to inform the design of a wearable prototype and to identify common snowboarding mistakes that the envisioned system should address (see section 4.2). An initial field study helped us to validate the concept and to experiment with different sensors that could measure a snowboarder’s posture and movements (see section 4.3). Finally, we have conducted a user study with snowboarders to collect sensor data during descents and to investigate if our wearable system could sense and classify basic context information that was required for interpreting body movements and for recognizing snowboarding mistakes (see section 4.4). These findings were presented in [Spelmezan et al., 2009c].

We have built a wearable snowboard training system.

We have focused on sensing and classifying basic context-information while snowboarding.

4.1 Interviews with Snowboard Instructors

Interviews with snowboard instructors informed the design of a wearable assistant for snowboard training.

To understand how snowboard instructors conduct courses and to gain insight into the most common mistakes in snowboarding, we have interviewed six instructors who taught introductory and advanced courses. Four instructors were members of the SNOW SPORT Team of RWTH Aachen University. These nonprofessional instructors had passed a training course that corresponded to the level of basic education (DSV Grundstufe) offered by the German Ski Association [Deutscher Ski-Verband (DSV), 2009]. One interviewee had a similar qualification (ÖSV Grundstufe) from the Austrian Ski Federation [Österreichischer Skiverband (ÖSV), 2009]. The other interviewee was a professional snowboard instructor (ÖSV Snowboardlehrer). These interviews were conducted primarily by Guggenmos [2007].

The instructors confirmed that snowboard students receive delayed feedback.

All instructors confirmed that snowboard students usually receive delayed feedback on their performance. A student only receives immediate feedback when they slowly descend together with the student during the first lessons. Sometimes, they call aloud from the distance if the student is close enough to hear the message. The instructors also mentioned that they cannot simultaneously observe all students when the group descends at the same time. In particular, when they focus on one student, the other students do not receive feedback on their performance.

Snowboard beginners face many challenges.

The instructors explained several difficulties and common riding mistakes that snowboarders face. The unfamiliar riding experience on the sliding board is challenging because both feet are fixed to the board. For this reason, many beginners are afraid to fall. They tend to ride in a stiff posture, they dangle their arms, they look at their feet, and they often bend their upper bodies downward from the waist instead of to flex the legs. Two mistakes are very common: snowboarders incorrectly distribute their weight and incorrectly rotate their upper bodies during turns. Although all these aspects contribute to a smooth and graceful riding style, maintaining correct weight distribution and upper body rotation are fundamental to learning the basic snowboarding skills.

We asked the instructors on their opinion on a wearable assistant that sensed the rider's posture and movements and that automatically provided feedback to correct the aforementioned mistakes while descending the slope. To avoid bias, we did not mention how the system could provide feedback.

Realtime feedback could help athletes to improve their riding skills and could assist coaches during courses.

The instructors agreed that immediate feedback during exercises could help snowboarders to improve their skills. Beginners would often perceive their posture and movements differently from what the instructor observed, and they would have difficulty to recall after the ride which movements they performed. For these reasons, realtime feedback could allow students to focus on a particular mistake and to compare their perceived posture to their actual posture. Also, many exercises would be performed on short sections of the slope because the coach cannot observe students who are far away. With automatic feedback, the group could avoid frequent stops.

Even so, the instructors mentioned that not all students would benefit from feedback during exercises. For example, some beginners would feel distracted if the instructor called out at them. Others would not notice or would not respond to spoken instructions issued during the ride because they focus on keeping their balance, or they pay attention to other things.

Some students do not notice when the instructor calls out at them.

When asked what type of feedback they suggested for communicating instructions to snowboarders during descents, our interviewees most often mentioned spoken messages over earplugs. These messages, however, might be difficult to perceive in the noisy outdoor environment, and they might block auditory warning signals of ski-slope grooming machines.

The instructors imagined spoken instructions, ...

Another interviewee mentioned goggles with built-in displays. Similar to off-line video analysis, a virtual snowboarder could demonstrate correct technique. This visual feedback, however, might overload the visual channel and might disturb snowboard students during descents.

visual demonstrations, ...

One interviewee mentioned gloves with buzzers that could encode instructions as different numbers of pulses: one pulse could signal to flex the legs, whereas two pulses could signal to stretch the legs. Continuous pulses could indicate that the proper movement range was left. Even so, students might have difficulty in counting the number of pulses. Therefore, he proposed instructions encoded as low and high frequency tones: a low tone could signal to flex the legs, whereas a high tone could signal to stretch the legs.

and buzzers to communicate feedback in realtime.

When we proposed artificial tactile instructions that could be delivered by vibration motors to those body locations that had to be adjusted, our interviewees laughed and made jokes about electro shocks. In general, they found this idea unusual but potentially valuable. Even so, they argued that artificial vibration delivered to the body might be hard to perceive because snowboarders were already exposed to vibration and tactile stimuli that naturally occurred during descents. Inexperienced and first-time snowboarders who were not familiar with tight clothes and with cold or swollen limbs might miss such tactile instructions. Therefore, this feedback might be more appropriate for advanced riders who already had experience in snowboarding. Advanced snowboarders would not constantly focus on maintaining balance such that they might have free attentional resources to perceive and process instructions while descending the slope. Such tactile instructions, however, should be clear to interpret, and they should only indicate one mistake at a time. In particular, this feedback should not overwhelm or annoy beginners who would often only need more time and practice for learning to snowboard.

Tactile instructions might be more appropriate for advanced riders.

Some interviewees stated that they could benefit from a wearable assistant themselves to fine-tune their own movements. Besides snowboarding, other sports that involved continuous body movements could also benefit from this approach, such as horse riding, swimming, surfing, or ice-skating. In contrast, football, volleyball, and sports that involved opponents and that required athletes to quickly adapt to new situations were considered less suited for wearable assistants that provided feedback in realtime.

Instructors could benefit from a wearable assistant themselves.

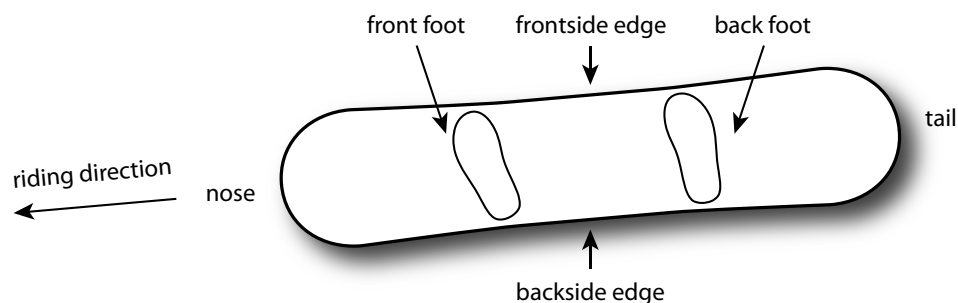


Figure 4.1: Snowboard terminology and typical stance when the left foot points forward (*regular stance*). Alternatively, some people prefer to ride with the right foot pointing forward (*goofy stance*).



Figure 4.2: Left: The neutral position on the snowboard. Middle: A frontside turn. Right: A backside turn. Photos by Martin Schliephake [Deutscher Verband für das Skilehrwesen, Interski Deutschland, 2003].

4.2 Common Mistakes in Snowboarding

In this section, we will first introduce the correct posture for the basic riding technique that snowboard students learn during a snowboarding course. Then, we will describe the aforementioned riding mistakes in detail, in particular incorrect weight distribution and *counter-rotation* [Deutscher Verband für das Skilehrwesen, Interski Deutschland, 2003].

The snowboard

A snowboard has two edges and resembles a wide ski. Both feet are fixed to the board such that the stance is transverse to the direction of travel. Fig. 4.1 illustrates this stance on the snowboard.

The neutral position describes the correct riding posture.

The *neutral position*, also called *basic stance*, describes the correct posture during descents (see Fig. 4.2, left). The weight is central over the board and distributed evenly between the feet. Ankles, knees, and hip joints are slightly flexed. This flex acts as natural suspension to compensate for uneven terrain, such as bumps in the riding path. The shoulders and the hips are in line with the feet's stance on the snowboard. The head is up, and the rider looks in the direction of travel. In general, snowboard instructors refer to this neutral position for recognizing mistakes during the ride.

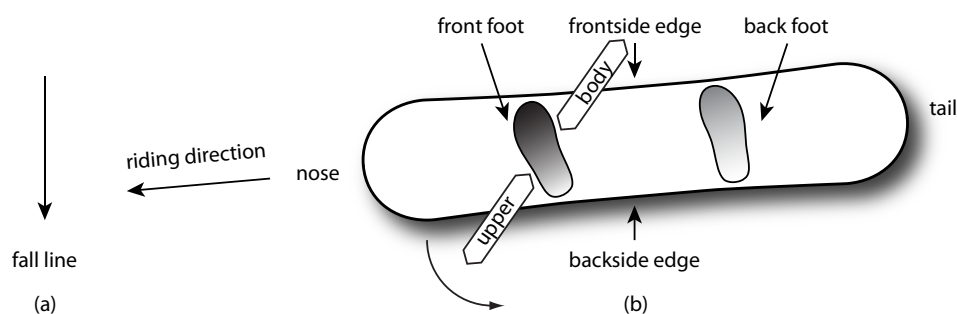


Figure 4.3: (a) The fall line is the most direct path that a ball would roll down the hill. (b) The shaded areas of the feet indicate the correct weight distribution for pivoting the board. Darker shades represent increased pressure. The white bars represent the orientation of the upper body, which turns towards the new riding direction, in this example towards the left.



Figure 4.4: Typical mistakes during turns are incorrect weight distribution (left) and counter-rotation (right). Photos by Martin Schliephake [Deutscher Verband für das Skilehrwesen, Interski Deutschland, 2003].

Descending the slope involves a sequence of turns that alternate between riding on the *frontside edge* and riding on the *backside edge*. These turns are called *frontside turns* and *backside turns* (see Fig. 4.2, middle and left). To switch between frontside and backside turns the rider points the board downhill and pivots the board across the *fall line* (see Fig. 4.3 (a)).

Frontside turns
and backside
turns

The basic technique for pivoting the board is called *basic turn*. This turn involves a sequence of body movements. Assuming a regular rider who descends on the *frontside edge* in neutral position (see Fig. 4.2, middle), he shifts the weight to the *front foot* and rotates the upper body to the left, towards the new riding direction (see Fig. 4.3 (b)). The resulting posture with increased pressure towards the *nose* of the board leads the board to follow these movements; the snowboard aligns to the fall line and pivots to the backside edge. Immediately following these movements, the rider returns to neutral position. He redistributes the weight evenly between the feet and aligns the torso parallel to the board (see Fig. 4.2, right). For the next turn, the rider shifts the weight to the front foot and rotates the upper body to the right such that the board pivots to the frontside edge.

Pivoting the
board with basic
turns

Beginners shift their weight to the back foot while pivoting the board.

This movement sequence challenges beginners. Facing downhill, they hesitate to shift their weight to the front foot. Moreover, the board quickly accelerates when aligned towards the fall line. For these reasons, beginners tend to shift their weight to the *back foot*. Riding in this posture feels safer, but the increased pressure towards the *tail* of the board makes it difficult to pivot across the fall line and can lead to falls (see Fig. 4.4, left).

Beginners counter-rotate their torso while traversing the slope.

Many beginners also tend to twist their torso while traversing the slope (see Fig. 4.4, right) instead of to keep their upper bodies parallel to the snowboard as required in neutral position. In this twisted posture, they cannot further rotate their torso towards the new turning direction for pivoting the board. Instead, they quickly pull the board across the fall line by simultaneously twisting the torso in the opposite direction of the new turn and by exerting force through muscle action of the legs and feet.

Beginners remain stiff and ride with straight legs.

In addition, many snowboarders often cannot assess if they sufficiently bend their legs. They keep their legs straight, and they bend the upper body downward from the waist. In general, people who learn motor skills tend to consciously control their movements and adopt a stiff posture to maintain balance [Wulf, 2007]. In snowboarding, riding with straight legs is not a mistake per se, but knee flexion improves balance and stability during the ride. Knee flexion also allows the rider to control the edging angle between the board and the slope. Also, for some techniques, the rider has to flex (stretch) the legs before pivoting and to stretch (flex) the legs after pivoting [Deutscher Verband für das Skilehrwesen, Interski Deutschland, 2003].

4.3 Initial Testing of the Technology

The first field study for sensing posture and motion on the snowboard

After interviewing the instructors, we decided to focus on the aforementioned snowboarding mistakes—incorrect weight distribution and counter-rotation—and on riding with straight legs. After prototyping our first sensing platform (see section 3.1.1), we conducted an exploratory pilot study with snowboarders in the indoor ski resort SnowWorld Landgraaf, The Netherlands. We experimented with different sensors to explore if it was possible to sense knee flexion, the weight distribution, and the rotation of the torso. Moreover, we recorded a first set of sensor data and footage for off-line data analysis. This work was done in part by Guggenmos [2007].

4.3.1 Hardware and Sensor Setup

Bend sensors measured the flexion of the legs.

Piezoresistive bend sensors that increase their resistance when deformed measured the amount of knee flexion during the ride. We used the Bend-Short v1.1 bend sensors (87 mm × 7 mm × 0.1 mm), which measured flex angles between 0° and 180° [Infusion Systems, 2007]. We wrapped two sensors in foam to increase their robustness and attached them to the back of each knee with knee pads (see Fig. 4.5).



Figure 4.5: Elastic supports fixated bend sensors at the back of the knees to measure the amount of knee flexion during the ride.

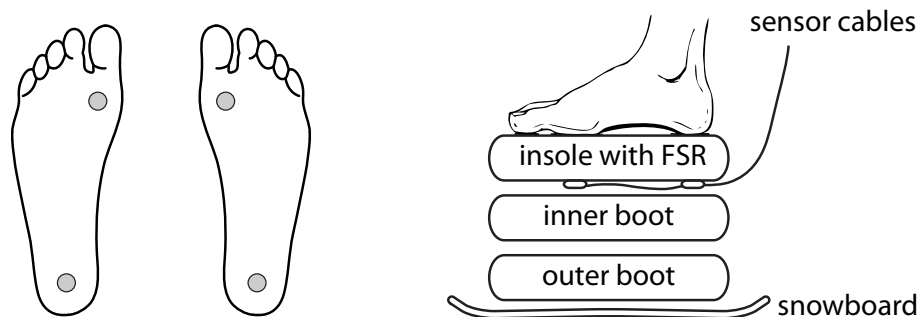


Figure 4.6: Pressure sensors located under the balls of the feet and under the heels measured the weight distribution on the snowboard.

Force-sensitive resistors (FSR) measured the amount of pressure applied by the feet and captured the weight distribution on the snowboard. We used the TouchMicro-10 v1.0 [Infusion Systems, 2007]. The sensors had a diameter of 10 mm, were 0.2 mm thick, and handled forces up to 667 N (68 kg). One FSR was placed under the first metatarsal bone to measure the pressure under the ball of the foot. Another FSR measured the pressure under the heel. We taped these sensors to insoles (0.4 mm thick) and inserted these insoles into the snowboarding boots (see Fig. 4.6).

Force sensors measured the weight distribution.

The angular difference between the snowboard and the upper body can reveal if the rider counter-rotates the torso. To measure the twist of the upper body relative to the snowboard, we used the Shake SK6, which is an off-the-shelf sensing unit that can output the compass heading in degrees (see Fig. 2.2, left). We attached one unit to the lower leg of the front foot and another unit to the upper body with hook and loop fasteners.

Two digital compasses measured the rotation of the upper body and the snowboard.

Fig. 4.7 shows our prototype system. Our sensor box (see also Fig. 3.2) interfaced with the two bend sensors and with the four FSR sensors. The host device, a Nokia N70 mobile phone, communicated wirelessly with the sensor box and with the two Shake SK6 devices over Bluetooth.

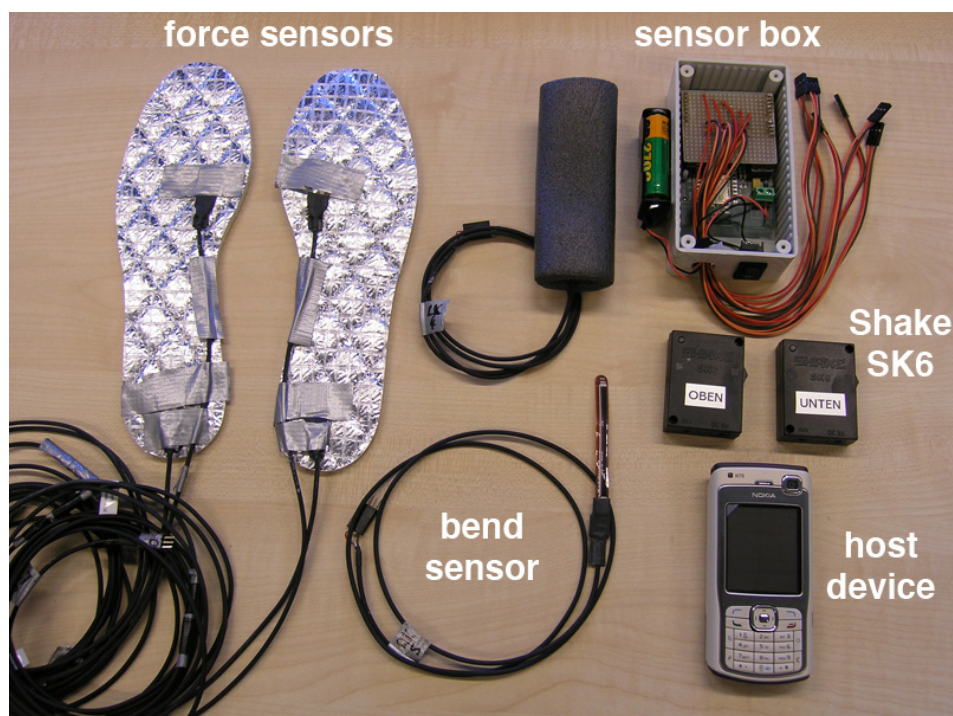


Figure 4.7: The first wearable system for sensing posture during descents comprised two force sensing insoles, two bend sensors, the sensor box, two Shake SK6 sensing units, and a Nokia N70 mobile phone as host device.

4.3.2 Participants and Study Procedure

Three advanced beginners participated.

Three snowboarders aged 24, 25, and 27 years participated (one woman). One volunteer snowboarded for nine years. The other two volunteers snowboarded for one year and for three months respectively. They rated their skills as advanced beginners and stated to snowboard between 1–3 weeks per year during their holidays.

The host device logged sensor data at 20 Hz.

The participants carried the sensor box in a pouch around their waist and the host device in a pocket of their ski suit. The host device logged raw sensor data streamed at 20 Hz from the three sensing units.

The neutral position served as reference pose to identify mistakes.

We have mentioned that the neutral position can be used for identifying snowboarding mistakes (see section 4.2). To compare the posture while descending the slope to the correct posture as required for basic turns, we instructed the participants to pose in this posture on level ground while the host device took a snapshot of the sensor data. These measurements served as *reference values* for off-line video analysis.

The descents were captured on video.

After this setup phase, we instructed the participants to descend a short section of the slope (about 60 meters, 200 ft), riding as they usually did. This setting was similar to what instructors would typically observe during courses if they were not too far away from their students. For each participant, we captured several descents on video to compare their pos-

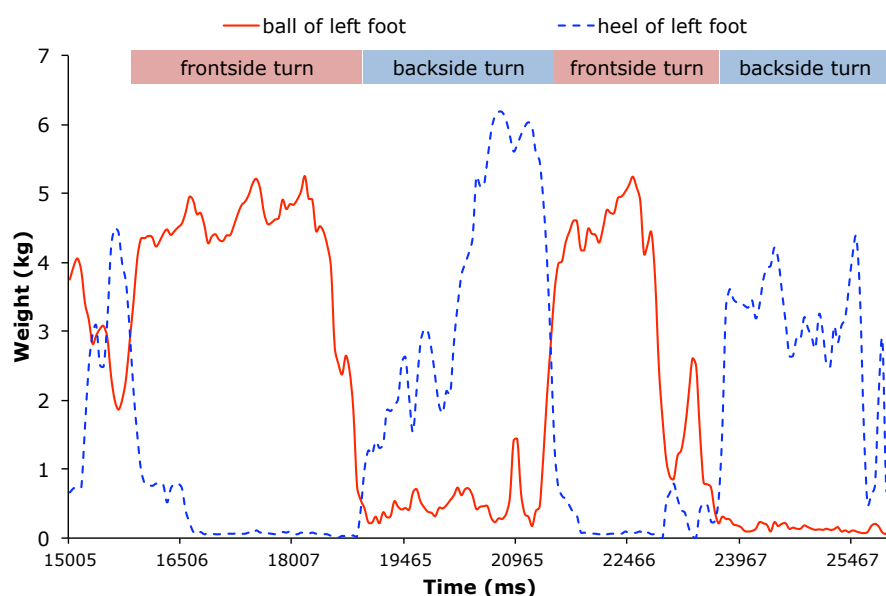


Figure 4.8: A participant’s weight distribution under the left foot. Frontside turns corresponded to increased weight under the ball of the foot. Backside turns corresponded to increased weight under the heel.

ture and body movements to the corresponding sensor measurements. The participants were instructed to perform a small jump before each descent. The force sensors detected this jump, which allowed us to synchronize the footage with the sensor recordings off-line in iSense (see Fig. 3.7).

4.3.3 Preliminary Results

Adjusting all sensors properly to the body and into the boots lasted one hour for each participant. Although the participants stated to have noticed the sensor cables under the insoles and the foam at the knees, the equipment did not hinder them in moving their bodies during the ride.

The sensing system did not cause discomfort.

The wireless sensing platform worked reliably on the slope. We did not experience data loss or Bluetooth connection problems between the host device and our sensor box. Even so, it was difficult to connect to the Shake SK6 over Bluetooth through the thick layer of clothes. Also, we found that our sensor box’s thin plastic connectors for sensors were too flimsy to withstand extended stress.

Some minor problems with the sensing platform

We did not experience problems with the force sensors inside the boots. The bend sensors, however, work best when bent around a radius of curvature. Although we embedded these sensors in a layer of foam to make them more robust, they showed sharp bending points after the study. These bending points lead to a sudden drop of sensor readings as opposed to continuous change while flexing the legs. One bend sensor was damaged.

The bend sensors were fragile.

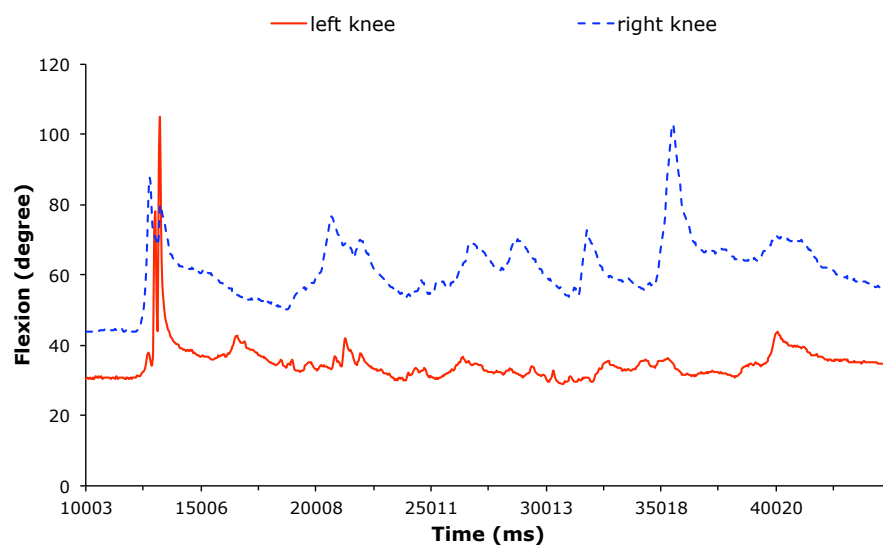


Figure 4.9: A participant’s amount of knee flexion during descents. The foam and the knee pads bent the sensors and introduced an offset between the flexion measured at the left and right knee. The true flexion was about 33.4° lower for the left knee and 44° lower for the right knee. The rapid increase in flexion at 13 seconds corresponded to the initial jump into the air before descending the slope. Overall, the left leg remained rather stiff compared to the right leg, which was slightly bent and stretched. The sharp increase in flexion at 35.5 seconds was an artifact. The footage did not confirm that the rider bent his right leg at that time.

The force sensors sensed the riding edge.

Off-line data analysis revealed that it was possible to differentiate between frontside and backside turns based on the weight distribution between the balls of the feet and the heels (see Fig. 4.8). We found that the reference values measured by the force sensors while posing in neutral position worked as threshold values for a threshold test that could estimate the point in time when pivoting the board: when the rider switched to the frontside edge, the sensor values under the balls of the feet exceeded their threshold values, whereas the sensor values under the heels dropped below their threshold values; when the rider switched to the backside edge, the sensor values under the heels exceeded their threshold values, whereas the sensor values under the balls of the feet dropped below their threshold values.

The sensor recordings revealed knee flexion.

The bend sensors revealed the amount of knee flexion (see Fig. 4.9). Similar to the weight distribution, the reference values recorded in neutral position with slightly bent legs worked as threshold values such that it was possible to determine when the participants stretched or flexed their legs.

The digital compass did not reveal the rotation of the body.

We also found that the compass heading of the Shake SK6 could not sense the rotation of the upper body and of the snowboard. These measurements were accurate in a stable environment, but the forces that continuously acted on the body during the ride and while pivoting the board skewed the accelerometer data and lead to heading errors [Caruso, 2000].

4.3.4 The Instructors' Opinion

Following the initial test on the slope, we presented the wearable system to eleven snowboard instructors and 28 ski instructors, including members of the SNOW SPORT Team. These instructors participated in the annual training course that was organized by the sports center of RWTH Aachen University [Hochschulsport der RWTH Aachen, 2007]. One certified snowboard instructor and three certified ski instructors led this course. We started by introducing all participants to our vision of wearable sports training systems that could analyze the athlete's body movements and that could provide tactile instructions for corrections. Then, we explained how our custom-built sensing systems worked, and we visualized sensor data collected during descents, including weight distribution (see Fig. 4.8) and amount of knee flexion (see Fig. 4.9).

Eight snowboard instructors (73%) and 19 ski instructors (68%) considered the idea to sense posture and body movements with sensors and to provide tactile feedback during descents to be potentially very valuable. The professional snowboard instructor agreed that the system could be useful for correcting counter-rotation and incorrect weight distribution. Even so, similar to the interviewed instructors (see section 4.1), he argued that advanced and proficient snowboarders were the target users. Beginners and advanced beginners might not benefit from realtime feedback because they tend to concentrate on maintaining their balance.

One ski instructor also taught dancing. He stated that he often placed himself behind a dancer to touch the dancer's right shoulder in the very moment when the dancer was supposed to move the right foot. Therefore, tactile instructions during descents might also work as reminders even if they were not delivered to those body locations that had to be adjusted.

The other participants mainly questioned whether an automatic system could recognize mistakes. One professional ski instructor argued that it would be impossible to distinguish between correct and incorrect movements without considering the characteristics of the slope. Movements that were correct in one situation could be wrong in a different situation. For this reason, analyzing posture without considering this context information would not yield which movements were wrong. For example, the instructor has to see the gradient of the slope in order to assess if the student sufficiently bends the legs. He further stated that beginners often ride with straight legs because they cannot maintain their balance otherwise. In such a case, realtime feedback for flexing the legs would not help. Even so, he agreed that knee flexion could be correlated with weight distribution; feedback based on this correlation could help athletes to improve their skills. Also, our approach could be useful for sports that involved simple and standardized movements, such as for fitness activities at the gym.

These comments indicated that our system would have to consider environmental context information for detecting riding mistakes. Even so, some

We demonstrated our initial results to a group of snowboard and ski instructors.

The majority of instructors liked our concept.

The correct posture during descents also depends on the characteristics of the slope.

mistakes do not depend on the properties of the slope. Moreover, the snowboard instructor who supported our idea argued that realtime instructions could help snowboarders to correct counter-rotation and incorrect weight distribution. His opinion encouraged us to conduct a formal study on the slope and to focus on recognizing the riding edge and transitions between frontside and backside turns. With this context information, the system could automatically determine the valid set of body movements and the correct timing of these movements during turns.

4.4 Sensing Basic Context Information While Snowboarding

We focused on sensing and classifying the riding edge.

The most basic context information that a wearable snowboard training system would have to sense and classify is whether the snowboarder descends on the frontside or backside edge. Based on this information, the system could infer if the rider's posture and movements are correct.

The correct upper body rotation depends on the rider's stance and on the riding edge.

The riding edge determines the set of valid upper body movements. Riders who prefer to descend with the left foot pointing forward have to turn the upper body to the left when they pivot from the frontside edge to the backside edge (see Fig. 4.3); they have to turn the upper body to the right when they pivot from the backside edge to the frontside edge. These movements are reversed for riders who prefer to descend with the right foot pointing forward; they have to turn the upper body to the right (left) when they pivot to the backside (frontside) edge.

Correct timing of body movements

The point in time when the snowboard pivots from one edge to the other edge reveals the correct timing of movements, including weight distribution, upper body rotation, and knee flexion. Snowboarders should rotate their torso towards the new riding direction shortly before pivoting the board, as rotation while traversing the slope can result in to counter-rotation (see Fig. 4.4, right). They should rotate their torso back to neutral position after pivoting the board. Likewise, they should shift their weight to the front foot shortly before pivoting the board and back to neutral position shortly after pivoting the board. Unless riding in deep snow, which would require them to keep the weight on the back foot such that the nose of the snowboard does not sink in, increased weight towards the tail of the snowboard while traversing the slope is considered wrong technique. The correct timing of knee flexion also depends on the time when the rider pivots the snowboard. Flexion or extension of the legs should occur shortly before pivoting and shortly after pivoting the board (see section 4.2).

We developed an algorithm that classified the riding edge.

For these reasons, our main objective was to develop an algorithm that could detect when snowboarders pivoted the board and that could classify turns either as frontside turns or as backside turns. Therefore, we collected force sensor data from several snowboarders for off-line data analysis. In addition, we tested an alternative sensor for classifying knee flexion in or-



Figure 4.10: Left: Optical bend sensors are robust and exhibit a linear response to flexion. The layer of foam shielded and fixated these sensors at the back of knees. Middle: Three force sensors captured the weight distribution. Right: The participants wore the SensAct box in a pouch.

der to correlate knee flexion to the instant when pivoting the snowboard. Finally, we evaluated a simple algorithm for activity recognition in order to detect when snowboarders descended or paused, based on accelerometer data. The motivation to differentiate between these activities was to prevent the wearable assistant from providing feedback on seemingly wrong posture, such as when moving the body during pauses. The work presented in this section was done in part by Schanowski [2008] under the guidance of the author.

4.4.1 Hardware Setup

Our first prototype of the sensor box reliably logged data during the pilot study, but the plastic connectors for sensors were too fragile for outdoor use (see Fig. 3.2). Therefore, we modified the design of the sensing platform and replaced the plastic connectors with TRS connectors (see Fig. 3.4). The redesigned SensAct box also included a motor shield that could control actuators, such as LEDs or vibration motors (see Fig. 3.3).

We also reconsidered the choice of sensors for measuring knee flexion. The thin piezoresistive bend sensors could result in artifacts in the sensor data if they were sharply bent (see Fig. 4.9). To avoid such artifacts, we built optical bend sensors [Kuang et al., 2002]. These optical sensors (see Fig. 4.10, left) consisted of a piece of plastic optical fiber with an LED at one end and a photocell at the other end. The fiber was abraded in the middle such that light sent through the fiber could escape when the fiber was bent: the more the fiber was bent, the more light could escape through the abraded region, and the less light arrived at the photocell. The redesigned SensAct box was appropriate for interfacing to these sensors; we powered the LEDs through the plugs that were originally intended for vibration motors.

Moreover, we included an additional force sensor inside each boot. This sensor was placed under the fifth metatarsal bone, which lies towards the outside of the ball of the foot (see Fig. 4.10, middle). We expected that these six sensors would capture the weight distribution between the left foot and the right foot, as proposed for skiing [Michahelles and Schiele, 2005].

The redesigned sensor box included a motor shield that could drive actuators.

Optical bend sensors measured knee flexion.

Three FSRs measured the weight distribution.

4.4.2 Participants and Study Procedure

The participants had different riding skills.

To record sensor data during descents, we conducted a study in the indoor ski resort SnowWorld Landgraaf, The Netherlands. Eight snowboarders aged 23–27 years ($M = 25.13$ years, one woman) were recruited from the local university. On a five-point scale ranging from beginner to expert, one participant rated his riding skills as level one, two as level two (advanced beginner), three as level three (advanced), and two as level five. They snowboarded on average 1–2 weeks per year. Four participants had attended a training course to improve their riding skills. One expert snowboarder was a member of the SNOW SPORT Team. Two other candidates served as pilot testers to reveal unforeseen problems with the hardware setup.

The host device logged sensor data at 50 Hz.

The participants wore the SensAct box in a pouch (see Fig. 4.10, right). The SensAct box sampled and streamed sensor data to the host device at 50 Hz. These measurements comprised data from six pressure sensors, two bend sensors, and one 2D accelerometer attached to the upper body.

We captured the rider's posture in neutral position as reference values.

Before the first descent, we instructed the participants to pose in neutral position on level ground (see section 4.2). To capture this posture, the system recorded reference values from all sensors for ten seconds. We chose this duration in order to capture the slight variations in sway while standing still, instead of recording only a snapshot of the sensor values as we did in our first field study (see section 4.3).

The participants descended a section of the slope and tried different riding techniques.

We recorded the participants on video for off-line data analysis. The distance between the starting point on the slope and the camera was about 140 meters (460 ft). This distance allowed the participants to gain higher speed and to perform more turns compared to the first field study. All participants descended five times. For the first and the last descent, we asked them to descend as usual. For the second descent, they had to shift the weight to the front foot for turning the board and to avoid incorrect weight distribution towards the back foot. For the third descent, we introduced an alternative riding technique that required them to stretch the legs before pivoting the board and to flex the legs after pivoting. This technique served to verify if the optical bend sensors sensed knee flexion and to observe how accurate our candidates performed these movements. For the fourth descent, they had to alternate between riding three turns and pausing for 10 seconds. All descents were performed without prior training.

4.4.3 Classification of the Riding Edge and of Turns

Comparing live sensor values to reference values

As depicted in Fig. 4.8, the force sensors inside the boots revealed when the balls of the feet and when the heels exerted pressure on the snowboard. To classify turns as frontside turns or as backside turns based on this sensor data, we implemented an algorithm in iSense (see Fig. 3.7) that compared the measurements during descents to the reference values captured in neutral position when the weight was evenly distributed between the balls of

the feet and the heels. The algorithm worked as follows:

First, the average of the reference values recorded under the balls (B) and the heels (H) of the left foot (L) and the right foot (R) were computed:

$$\bar{R}_i, i \in \{LB, LH, RB, RH\}$$

At each sampling time t during descents, *mean shifting* adjusted the force sensor values $F_i(t)$ by subtracting the corresponding reference values \bar{R}_i . As a result, the value 0 became the new reference value for all measurements, which indicated when the weight was evenly distributed between the balls of the feet and the heels:

$$Y_i(t) = F_i(t) - \bar{R}_i$$

Simple *exponential smoothing* with smoothing factor α ($0 \leq \alpha < 1$) reduced sensor noise for the adjusted values $Y_i(t)$:

$$\begin{aligned} S_i(0) &= Y_i(0) \\ S_i(t) &= \alpha \times S_i(t-1) + (1 - \alpha) \times Y_i(t) \end{aligned}$$

The algorithm then summed the forces measured under the balls of the feet (B) and the heels (H) and computed the difference (D) between these values:

$$\begin{aligned} B(t) &= S_{LB}(t) + S_{RB}(t) \\ H(t) &= S_{LH}(t) + S_{RH}(t) \\ D(t) &= B(t) - H(t) \end{aligned}$$

Simple *moving average* (SMA) returned the mean weight distribution between the balls of the feet and the heels (the *window size* w denoted the number of previous samples used to compute the mean weight distribution):

$$E(t) = SMA_w(D(t)) = \frac{D(t) + D(t-1) + \dots + D(t-w+1)}{w}$$

The value of $E(t)$ could be used for determining the riding edge. A threshold value T_E defined the tolerance range around the reference value 0 where we regarded the weight distribution between the balls of the feet and the heels to be evenly distributed as captured in neutral position. The rider descended on the frontside edge if the mean weight distribution was towards

A threshold test determined the riding edge.

the balls of the feet: $E(t) > T_E$. The rider descends on the backside edge if the mean weight distribution was towards the heels: $E(t) < -T_E$. The rider pivoted the board if the mean weight distribution was within the boundaries of the tolerance range defined by the positive and negative threshold values: $-T_E \leq E(t) \leq T_E$. Transitions between the edges corresponded to the beginning of turns.

Parameters for classifying the riding edge.

The precision of this algorithm in classifying the riding edge depended on three parameters: the smoothing factor α , the window size w , and the threshold value T_E . To narrow down the choice of values that could be used for classifying turns, we first experimented with the following values that were applied to the sensor recordings from the first field study: $T_E \in \{50, 100, 150, 200\}$, $w \in \{5, 10, 20, 40\}$, $\alpha \in \{0.0, 0.3, 0.5, 0.7, 0.9\}$ (the 10-bit analog to digital converter of the Arduino BT board mapped input voltages between 0 and 5 V from the sensors to integer values between 0 and 1023; $T_E = 50$ corresponded to 244 mV or roughly 0.4 kg for the chosen force sensors; $w = 5$ corresponded to 250 ms at 20 Hz sampling rate). In general, we found that lower values for the threshold and for the window size decreased the delay for recognizing new turns but caused classification errors. The effect of the smoothing factor was less obvious to determine.

The first descents served as training set to optimize the recognition accuracy of the algorithm.

To analyze the new sensor recordings and to optimize the recognition rate of our algorithm across all riders, we decided for applying $T_E = 50$, $w = 25$ (500 ms at 50 Hz), and $\alpha \in \{0.1, 0.2, \dots, 0.9\}$. The first descents served as training set. We compared the output of the algorithm to the riding edge on footage. We counted the number of correctly classified turns (true positives), missed turns (false negatives), and misclassified turns (false positives). These values served for calculating a ranking R for each smoothing factor α . A high ranking corresponded to a high number of correctly classified turns and to low numbers of missed and misclassified turns:

$$R_\alpha = \#correct - \#missed - \#misclassified$$

The last descents served as test set.

Given the smoothing factor α that yielded the best results, we evaluated the algorithm based on the sensor recordings of the participants' last descents.

Results

All turns of the training set were correctly recognized.

The classification accuracy for the training set was independent of the smoothing factor α . In total, the participants performed 56 turns. All turns were correctly classified as frontside turns or as backside turns as observed on footage. The algorithm reported three states: pivoting, frontside edge, and backside edge. Fig. 4.11 shows an example output.

96.72% of turns of the test set were correctly recognized.

Table. 4.1 summarizes the classification accuracy for the test set. In total, the participants performed 61 turns. A smoothing factor $\alpha = 0.9$ yielded the highest ranking $R_{0.9} = 57$ with 59 correctly classified turns (96.72%)

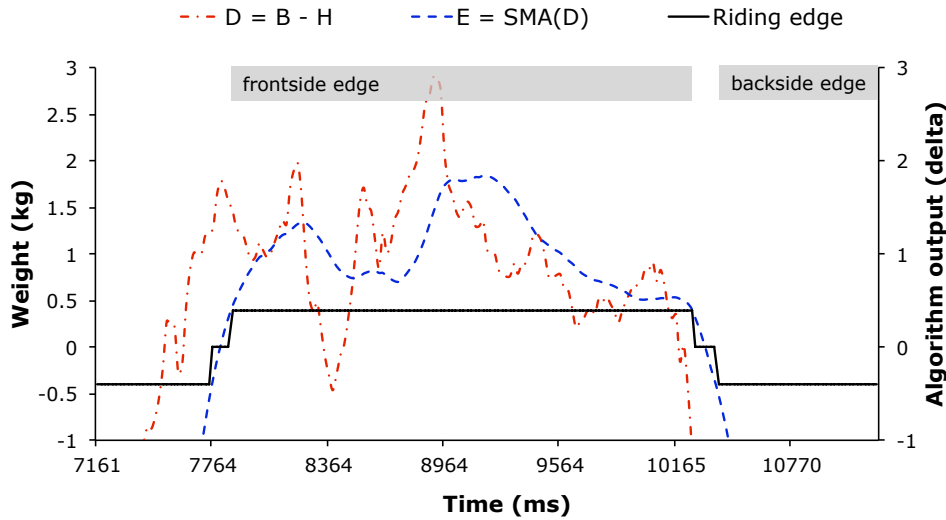


Figure 4.11: Example output of the algorithm that detected the riding edge. When the mean weight distribution E exceeded the threshold value $T_E = 0.4$, the algorithm outputted 0.4 to report turns on the frontside edge. When E fell below the negative threshold value $-T_E = -0.4$ kg, the algorithm outputted -0.4 to report turns on the backside edge. An output of 0 signaled an even weight distribution between the balls of the feet and the heels while pivoting the board ($-T_E \leq E \leq T_E$).

Table 4.1: The classification accuracy of the turn detection algorithm when applied to the test set. The results for $\alpha \in \{0.1, 0.2, 0.4, 0.5, 0.6, 0.7\}$ were the same as for $\alpha = 0.0$.

| Smoothing factor α | 0.0 | 0.3 | 0.8 | 0.9 |
|----------------------------|-------|-------|-------|--------------|
| Correctly classified turns | 56 | 55 | 57 | 59 |
| Misclassified turns | 5 | 6 | 4 | 2 |
| Ranking R_α | 51 | 49 | 53 | 57 |
| Recognition accuracy (%) | 91.80 | 90.16 | 93.44 | 96.72 |

and two false positives. The lowest ranking was $R_{0.3} = 49$ with 55 correctly recognized turns (90.16%) and six false positives. These false positives were temporarily misclassified turns, which we regarded as errors. In these few cases, the algorithm did not immediately recognize the new riding edge when the board was pivoted as observed on footage. Even so, the edge was correctly classified as soon as the snowboarder exerted sufficient pressure towards the balls of the feet or towards the heels while traversing the slope.

We have also implemented an algorithm that used sensor data from the six force sensors to compute the mean weight distribution between the left foot and the right foot. This algorithm worked analogous to the algorithm that classified the riding edge, except that the difference in weight distribution was computed between the sum of the forces measured under the left foot and under the right foot. We found, however, that this approach did not accurately estimate the weight distribution as observed on footage.

Analyzing the weight distribution between the feet did not yield usable results.

Discussion

The algorithm based on threshold tests.

The developed algorithm used a threshold test and empirically chosen parameters for classifying the riding edge. This method was simple compared to machine learning algorithms that would consider the variability in the sensor data (see section 2.2). Even so, 96.72% of turns were correctly recognized in the test set, which comprised sensor recordings from snowboarders with different riding skills. Our sensor setup used for recognizing the riding edge was similar to the setup used for recognizing different modes of walking with two force sensors placed under the shoes [Junker et al., 2004]. In this case, however, a probabilistic model based on Bayes classifiers differentiated between level walking, ascending stairs, and descending stairs with 98.2% accuracy on average. Future work should explore if similar algorithms could help improve the classification of turns. These algorithms, however, have to run on micro-controllers in realtime.

Our setup was prone to errors.

Although our algorithm correctly classified turns with high accuracy, we surmise that sensors built into the soles of the boots or sensors built into the snowboard could help improve the recognition accuracy. Overall, it was difficult for us to position the force sensors directly under the balls of the feet and under the heels because the form of the participants' feet and the form of their boots slightly varied. Although we verified the placement of these sensors with the Sensor Monitor application (see Fig. 3.6, left), some participants had to exert more pressure until their sensor values peaked. The sensor cables that run directly under the feet probably also influenced the measurements. Moreover, we recorded reference values in neutral position only before the first descent. Since the sensor measurements also depended on how tight the participants fastened their bindings before each descent, we surmise that capturing reference values before each descent could have improved the recognition accuracy of our algorithm.

We chose empirical values that yielded good results.

Besides improving the setup of the force sensors, it might be necessary to adjust those parameters that can influence the classification of turns, such as the window size w used for computing the mean weight distribution $E(t)$. For example, Fig. 4.11 shows a fluctuation of D around 8.3 seconds. Had the window size been too short, $E(t)$ would have fallen below the threshold value T_E such that the algorithm would have incorrectly interpreted this fluctuation as a new turn. During bumpy rides, a larger window size could smooth out such short-term fluctuations that might result in misclassified turns. More samples for computing $E(t)$, however, will decrease the responsiveness of the algorithm. Alternatively, hysteresis could help prevent the algorithm from misclassifying turns when $E(t)$ fluctuates around the threshold value.

The threshold value determines the sensitivity of the algorithm.

Also, the threshold value T_E could be adjusted to match different riding skills and riding techniques. T_E determines how sensitive the algorithm responds to weight shifts. With high thresholds, it might be possible to assess the quality of turns for advanced riders while *carving*; this riding technique requires the snowboarder to increase the edging angle (see Fig. 4.2, right),

which results in high pressure loads under the heels and under the balls of the feet. In contrast, low thresholds might detect when beginners pivot. Beginners usually slide down the slope because they do not have the skills to increase the edging angle. With low thresholds, a slight shift in weight towards the toes (heels) would yield the frontside (backside) edge. During bumpy rides, however, low thresholds might result in misclassified turns.

Our preliminary results indicated that it was not possible to classify whether the weight distribution was towards the left or right foot. We assume that the binding influenced the force sensor measurements. The front part of the binding fastened the boot to the snowboard and exerted a counter-force onto the balls of the feet. When the rider pulled the toes upwards during backside turns, the ball of each foot still exerted some pressure onto the sensors (see Fig. 4.8 between 19–21 and 24–25 seconds). In contrast, the heels could be lifted inside the boots during frontside turns; the sensors located under the heels did not measure forces such that these sensors' values approached 0 (see Fig. 4.8 between 16.5–19 and 22–23 seconds). A similar effect could have occurred when the rider increased the weight towards either foot; the binding would exert a counter-force onto the other foot, in particular under the ball of the foot. Future work should investigate if additional sensors per foot, sensors built into the soles of the boots, or sensors built into the snowboard could help to accurately measure and classify the weight distribution between the left and right foot.

The binding influenced the force sensor measurements.

4.4.4 Knee Flexion during the Ride

For the third descent, the participants were asked to stretch the legs before pivoting the board and to flex the legs after pivoting. The optical bend sensors attached to the back of the knees measured this flexion and extension (see Fig. 4.12). Our method for classifying knee posture and for differentiating between stretched and flexed legs was similar to our method for classifying the riding edge (see section 4.4.3). The algorithm computed the average of the reference values measured for the left knee (LK) and the right knee (RK) while posing in neutral position with slightly bent legs:

$$\bar{R}_i, i \in \{LK, RK\}$$

At each sampling time t during descents, mean shifting adjusted the bend sensor values $B_i(t)$ by subtracting the corresponding reference values \bar{R}_i (the value 0 became the new reference value, which represented slightly bent legs):

$$Y_i(t) = B_i(t) - \bar{R}_i$$

Simple exponential smoothing with smoothing factor α ($0 \leq \alpha < 1$) reduced sensor noise for the adjusted values $Y_i(t)$:

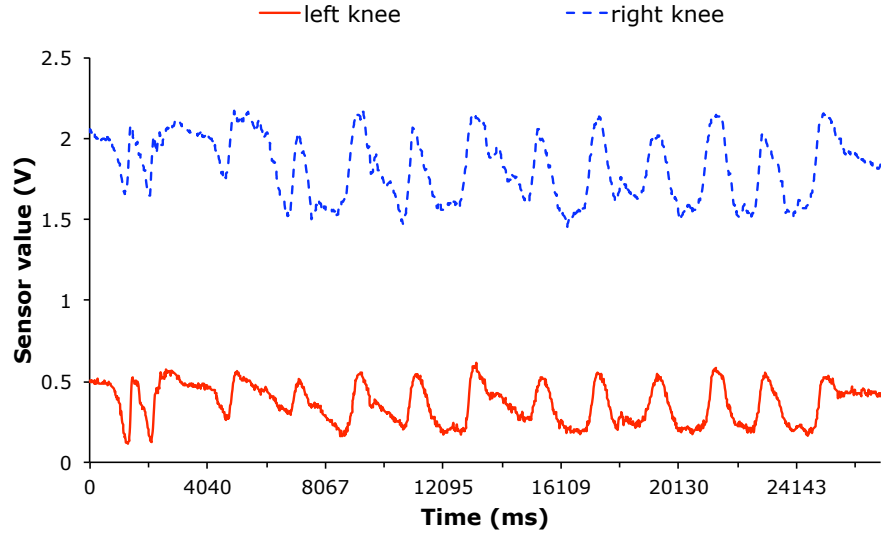


Figure 4.12: A participant’s amount of knee flexion measured with optical bend sensors. In this example, we did not map the sensor values to the corresponding flexion angles in degrees, as was the case with the piezoresistive bend sensors that were calibrated by the manufacturer to exhibit an identical response characteristic (see Fig. 4.9). Although we tried to build both optical bend sensors alike, the output range in volt depended on the width and depth of the abraded area on the optical fiber. Thus, this example shows a qualitative measure: a decrease in voltage corresponds to flexion of the legs, whereas an increase in voltage corresponds to extension of the legs. The foam and the knee pad introduced an offset between the flexion measured at the left and right knee (see also Fig. 4.9). The participant jumped between 1–2.5 seconds to point the board downhill.

$$S_i(0) = Y_i(0)$$

$$S_i(t) = \alpha \times S_i(t-1) + (1 - \alpha) \times Y_i(t)$$

The algorithm then summed the values for both knees (K) and computed the mean knee flexion (F , based on SMA with window size w):

$$K(t) = S_{LK}(t) + S_{RK}(t)$$

$$F(t) = SMA_w(K(t)) = \frac{K(t) + K(t-1) + \dots + K(t-w+1)}{w}$$

A threshold test determined the posture of the legs.

The value of $F(t)$ could be used for determining if the legs were flexed or stretched. A threshold value T_F defined the tolerance range around the reference value 0 where we regarded the legs to be slightly bent: $-T_F \leq F(t) \leq T_F$. The rider stretched the legs if the mean flexion was greater

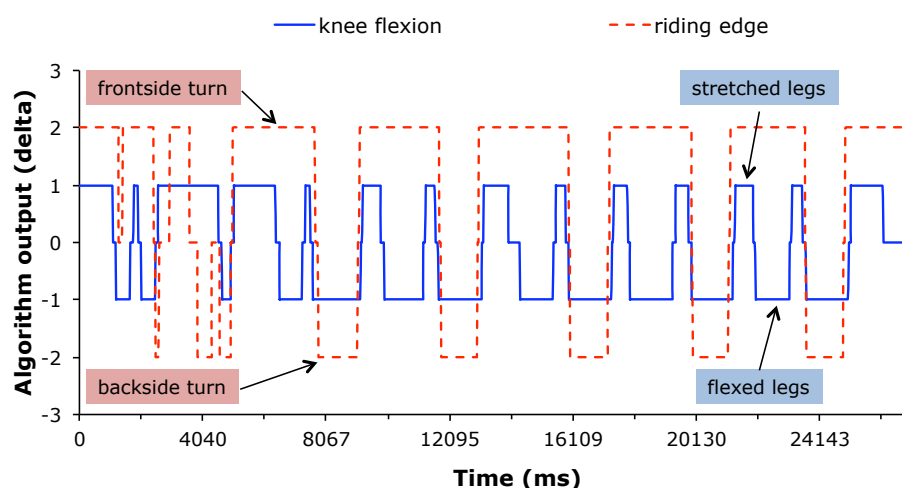


Figure 4.13: A participant’s knee posture when stretching and flexing the legs while pivoting the board (see Fig. 4.12 for the bend sensor values). The ordinate 0 corresponded to slightly flexed legs and to an even weight distribution while posing in neutral position. To visualize the relationship between knee flexion and the riding edge, stretched legs were mapped to the ordinate 1, flexed legs to the ordinate -1, frontside turns to the ordinate 2, and backside turns to the ordinate -2. The posture was unstable while gaining speed before the first turn at five seconds. As a result, the output of the algorithms fluctuated. The last turn occurred at 25 seconds.

than the threshold value: $F(t) > T_F$. The rider flexed the legs if the mean flexion was lower than the negative threshold value: $F(t) < -T_F$.

Results

Given the posture of the knees and the riding edge, it is possible to analyze the rider’s technique. Fig. 4.13 correlates knee flexion to the riding edge for one participant, based on an empirically chosen window size $w = 25$ samples (500 ms), $T_F = 10$ (48.83 mV), $T_E = 50$ (244 mV or 0.4 kg). In this example, flexion and extension of the legs coincided with pivoting the board, although the timing slightly differed depending on the riding edge. The participant stretched the legs while pivoting to the frontside edge and flexed the legs after pivoting; however, the legs were stretched before pivoting to the backside edge and flexed while pivoting.

A posture model of the legs for assessing snowboarding skills

The duration for riding with stretched and flexed legs and the length of the turns provided additional information on the participant’s skills. In particular, backside turns were noticeably shorter than frontside turns. This indicates that this participant preferred to ride on the frontside edge. In fact, backside turns can be more challenging than frontside turns, in particular for snowboard beginners. Overall, we observed that some participants did not succeed in flexing and extending their legs as required.

The threshold value determines the sensitivity of the algorithm.

As for the riding edge, the threshold value for knee flexion has to be chosen such that the movements of the legs can be differentiated. In the example given above, the output of the algorithm was similar for $T_F \in [0...20]$, which corresponded to thresholds up to 10% of the range between the minimum and maximum values of $K(t)$. With higher thresholds, the algorithm missed transitions between stretched and flexed legs.

Characteristics of optical bend sensors

Our custom-built optical bend sensors did not produce sharp increases in the measured voltage during the initial jump before descending the slope, as was the case with the piezoresistive bend sensors (compare Fig. 4.12 at 2.5 seconds to Fig. 4.9 at 13 seconds). Neither did they produce artifacts. We also found that these sensors were less susceptible to sensor noise than the piezoresistive bend sensors or the force sensors; in practice, we were able to skip exponential smoothing without influencing the classification of knee flexion. One bend sensor, however, broke at the abraded area. Also, the foam that fixated the sensors slipped out of the knee pads a few times.

Discussion

A simple posture model can reveal snowboarding mistakes.

Knee flexion in combination with turn detection nicely demonstrated that it was possible to build and to analyze a simple posture and motion model of the legs during descents. Once other body movements can be recognized with wearable sensors, including upper body rotation and the weight distribution between the feet, a wearable snowboarding assistant could provide instructions for correcting wrong movements and for signaling the correct timing of movements, as envisioned in section 1.1. Moreover, statistics such as the length of turns or the time difference between pivoting the board and performing the required body movements could offer additional feedback that could help coaches in assessing a snowboarder's riding skills.

4.4.5 Activity Recognition: Riding and Pausing

A wearable snowboarding assistant should provide instructions during descents but should remain idle during pauses. To test if data from an accelerometer would suffice to distinguish between riding and pausing, we measured the acceleration of the torso. We used the GForce3D-3 v1.0, which sensed acceleration between -3 G and 3 G [Infusion Systems, 2007].

The acceleration during the ride differs from the acceleration during pauses.

In general, acceleration patterns during descents should differ from acceleration patterns while standing still (see Fig. 4.14). The characteristics of these patterns could reveal if the snowboarder is riding or pausing. In this work, we summed the standard deviation of the acceleration measured vertical to the slope (Y), which captured up and down movements, and the standard deviation of the acceleration measured in direction of the ride (X), which captured left and right movements along the board, based on an empirically chosen window size of $w = 50$ samples (1 second).

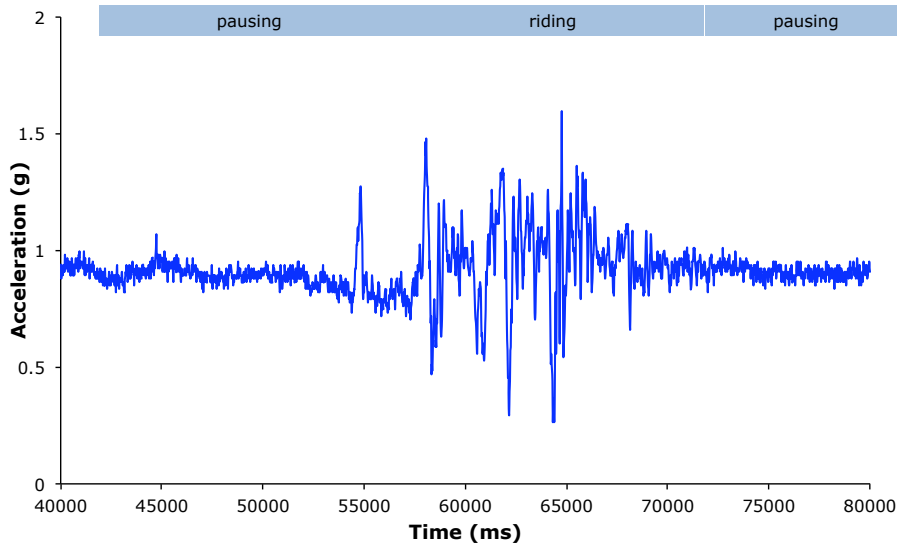


Figure 4.14: A participant’s acceleration measured along the vertical axis of the torso. At 55 seconds, the participant quickly turned her upper body towards the valley and continued to descend. She stopped at 70 seconds.

$$S(t) = \sigma_w^X(t) + \sigma_w^Y(t)$$

A threshold test determined the time during which the rider moved ($S(t) \geq T_A$) or stood still ($S(t) < T_A$).

Results

Overall, our approach to activity recognition recognized 96.03% of all descents and 77.78% of all pauses, based on an empirically chosen threshold value $T_A = 8$ (39 mV or 0.12 G). A lower threshold value ($T_A = 0.06$ G) increased the recognition of descents (99.89%) but decreased the recognition of pauses (50.16%). Misinterpretations of the activity occurred while riding at low speed, such as during the slow acceleration phase at the start of the ride, during the slow deceleration phase before coming to a halt, and when the participants moved the body after the board stopped.

The activity recognition based on a threshold test.

Discussion

In general, activity recognition involves machine learning algorithms that classify sensor data obtained from several accelerometers [Bao and Intille, 2004] (see also section 2.2). We used one accelerometer and a threshold test to differentiate between riding and pausing. This simple technique demonstrated that activity recognition is possible while snowboarding. Even so, our approach was prone to errors. In particular, upper body movements

Machine learning algorithms are better suited for classifying activity.

during pauses yielded classification errors. It might have been beneficial to also compare the acceleration of the upper body to the acceleration of the snowboard because the snowboard typically does not move during pauses. In this case, a threshold test might have differentiated between riding and pausing with higher accuracy.

4.5 Closing Remarks

We have sensed and classified posture and body movements while snowboarding.

In this chapter, we have informed the design of a wearable assistant for snowboard training. Based on two field-studies that focused on sensing of basic context-information for recognizing common snowboarding mistakes, we have presented and evaluated algorithms for classifying turns, knee flexion, and activity. Our results demonstrated that it was possible to build a simple posture and motion model of the body that could be used for assessing certain aspects of the quality of a snowboarder's riding technique. Overall, our findings serve as a starting point for building wearable systems that could automatically detect wrong posture and movements while descending the slope.

In the following chapters, we will focus our investigation on artificial tactile stimuli as a new method for providing instructions how to move the body during physical activities. To evaluate these tactile instructions in the field, we have used the aforementioned findings for implementing a simple wearable assistant for snowboard training. This system could sense and interpret the snowboarder's weight distribution between the balls of the feet and the heels for classifying the riding edge in realtime, and could automatically provide tactile instructions that indicated correct posture during turns.

Part II

Tactile Motion Instructions

Chapter 5

Fundamentals of Tactile Perception

“Touch seems to be as essential as sunlight.”

—*Diane Ackerman, A Natural History of The Senses*

In the first part of this dissertation, we have focused on wearable computing and on a custom-built sensing and feedback device. We have built this device as a basis for exploring artificial tactile stimuli as instructions how to move the body, and we have shown how this system could be used for sensing posture and body movements during physical activities.

We will now focus on tactile feedback. To design tactile instructions, we need to know how the skin processes tactile stimuli and which tactile sensations humans can perceive and differentiate. Therefore, in this chapter, we will introduce the anatomy of the skin. We will present technologies for generating tactile signals, and we will discuss design parameters for encoding information as tactile stimuli. Finally, we will summarize example applications that conveyed messages over the tactile sense.

5.1 The Cutaneous Sense

The skin is one of the most important organs of our body and indispensable to life. This thin layer of tissue protects us from infection and prevents the loss of body liquids. Moreover, the skin enables us to feel when something contacts our body. For example, our clothes create friction. We can discriminate whether the textile is scratchy or soft. When we sit in a chair, we notice its shape and feel both soft and hard areas, which can be padded textile or hard armrests. Other sensations that relate to the skin enable us to hold a pen with our fingers, to feel the applied pressure while writing, and to notice when we accidentally touch a hot surface.

The skin senses when something touches our body.

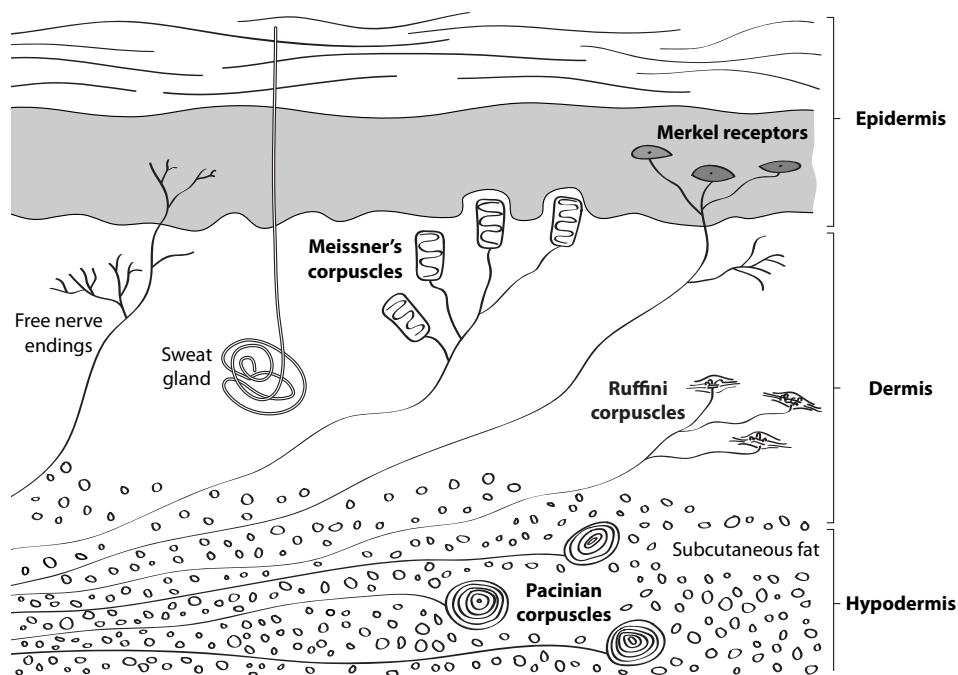


Figure 5.1: The three layers of the skin. Mechanoreceptors detect when the skin is deformed (adapted from [Goldstein, 2002]).

Receptors in the skin register external stimuli.

The skin consists of three layers: the epidermis, the dermis, and the hypodermis (see Fig. 5.1). Their thickness varies across the body. For example, these layers are thicker at the stomach and at the feet than at the eyelids. The *epidermis* is the upper layer and acts as barrier (0.55–1.5 mm thick). The *dermis* (0.6–3 mm thick) contains free nerve endings and receptors that respond to external stimuli. The nervous system transmits the information on these stimuli to the brain. This information can result in sensations including temperature, pain, pressure, or vibration. The *hypodermis* is the lowest layer. This tissue can be several centimeters thick and includes fat, connective tissue, blood vessels, and hair follicle roots.

Table 5.1: Mechanoreceptors have different characteristics that determine to which tactile stimuli they respond and which sensations we perceive ([Kaczmarek et al., 1991, Goldstein, 2002, Wall and Brewster, 2006]).

| | Merkel | Meissner | Ruffini | Pacinian |
|---|---------------------------|----------------------|--------------|---------------|
| Frequency range Hz (peak sensitivity) | 0–100 (5) | 1–300 (50) | < 8 (0.5) | 5–1.000 (250) |
| Rate of adaptation | SA1 | RA1 | SA2 | RA2 |
| Receptive field area mm^2 (median) | 1–100 (11) | 2–100 (12.6) | 10–1000 (59) | 10–500 (101) |
| Receptors/ cm^2 fingertip (palm) | 140 (25) | 70 (8) | 21 (9) | 9 (15) |
| Perceived sensation | Pressure, form, roughness | Stroking, fluttering | Skin stretch | Vibration |

The *tactile sense* pertains to our sensation of pressure [Oakley et al., 2000]. Four types of *mechanoreceptors* sense mechanical pressure and deformation, such as when the skin is stretched or pulled (see Fig. 5.1): *Merkel's discs* and *Meissner's corpuscles*, which can only be found in hairless skin; and *Ruffini's corpuscles* and *Pacinian corpuscles*, which can be found in hairy and in hairless skin. These receptors have different characteristics that enable us to distinguish between pressure intensities, textures, and other attributes of objects that we interact with.

The tactile sense

Table 5.1 summarizes important characteristics of these mechanoreceptors: mechanoreceptors respond to stimuli that deform the skin at different frequencies; they adapt slowly (SA) or rapidly (RA) to static stimuli; the size of their receptive fields is small (1) or large (2); their receptor density in the skin varies. These characteristics are discussed in the following paragraphs (for additional information on mechanoreceptors, see [Kaczmarek et al., 1991, Goldstein, 2002, Wall and Brewster, 2006]).

The main characteristics of mechanoreceptors

Mechanoreceptors fire impulses when they detect a stimulus. This firing rate tends to decrease with time. The rate of adaptation describes how fast they adapt to a stimulus that remains constant. Merkel's discs and Ruffini's corpuscles adapt slowly. They are most sensitive to a static stimulus, and they continue to respond until the stimulus stops. Merkel's discs respond to steady indentation and enable us to perceive the form and roughness of objects, including texture, edges, points, and corners. Ruffini's corpuscles respond to rapid indentation that typically stretches the skin.

Rate of adaptation

In contrast, Meissner's corpuscles and Pacinian corpuscles quickly adapt to static stimuli. They are most sensitive to dynamic stimuli and only fire impulses when they detect a change, which typically occurs at the beginning and at the end of the stimulus. The Pacinian corpuscles detect high frequency vibrations and optimally respond to frequencies around 250 Hz [Cholewiak and Collins, 1991, Verrillo and Gescheider, 1992].

Pacinian corpuscles detect high frequency vibration.

Mechanoreceptors respond to a stimulus that occurs within a certain area around their location in the skin. The size of this area—the receptive field—determines how distant and accurate they perceive the stimulus. Ruffini's and Pacinian corpuscles have large receptive fields. Although they best respond to a stimulus that occurs directly above their location in the skin, they also gather information from distant stimuli. This information, however, is less detailed and accurate. Merkel's disks and Meissner's corpuscles have small receptive fields. These mechanoreceptors only respond to a stimulus that occurs very close to them, but they yield precise perceptions.

Receptive field area

The fingertips and the lips, which we mainly use for exploring and interacting with objects, contain densely packed mechanoreceptors with small receptive fields. Mechanoreceptors with large receptive fields mainly exist in those areas of the body that do not require an accurate tactile sense, such as the back, the stomach, and the legs.

Receptor density

The density and the receptive fields of mechanoreceptors influence how close

Spatial resolution and two-point threshold

two points of stimulation can be such that we perceive them as different and not as one stimulus. The *two-point threshold*, a measure of the spatial resolution of the skin, denotes this minimum distance between two stimuli. This threshold varies on the body and ranges from 0.9 mm at the fingertips to 45 mm at the calf, the thigh, and the back [Weinstein, 1968].

5.2 Tactile Display Technologies

Force feedback devices address the kinesthetic sense.

The research literature differentiates between force feedback devices and tactile feedback devices [Oakley et al., 2000]. Force feedback devices address the human *kinesthetic sense*, which pertains to the relative position and movements of the body, including finger, hand, and limbs. Kinesthetic information originates from receptors located in muscles, joints, and tendons. For example, the Phantom Omni haptic device [SensAble Technologies, Inc., 2010] generates forces for touching and interacting with virtual objects on a computer monitor. If the user pushed the cursor against a virtual object, motors in the device would create counter-forces to indicate a solid. Other devices were designed for computer games, such as Logitech's Force 3D Pro joystick [Logitech, 2010].

Tactile feedback devices address the tactile sense.

In contrast to force feedback devices, tactile feedback devices address the tactile sense. This sense pertains to the mechanoreceptors that respond to deformations of the skin, such as when the skin is stretched or pulled. Tactile feedback devices are also called *actuators* or *tactors*. Those that vibrate are also called *vibrotactile* displays [van Erp, 2002]. Some devices were designed to optimally stimulate the Pacinian corpuscles because these receptors best respond to vibration.

Inertial actuators rotate an eccentric mass.

In this section, we will focus on mechanical devices that deform the skin in order to create tactile sensations. The most widely used actuators are *inertial actuators*, such as *vibration motors* that are built into mobile phones. These inexpensive actuators (3–5 Euros) are electric motors that rotate an eccentric mass [Mortimer et al., 2007]. Two types of vibration motors exist: *pancake* motors and *cylindrical* motors (see Fig. 5.2). They are typically shielded by a casing that vibrates together with the mass. Pancake motors are placed flat on the skin such that their eccentric mass rotates horizontally to the skin. The eccentric mass of cylindrical motors rotates perpendicularly to the skin. For this reason, cylindrical motors tend to produce slightly more intense sensations [Schätzle et al., 2006].

Limitations of inertial actuators

A disadvantage of many vibration motors is that they vibrate at frequencies below the peak sensitivity of the Pacinian corpuscles. Another disadvantage is that a higher supply voltage increases both the frequency and the intensity of the vibration. Also, since the mass rotates, the spin-up time to reach the full intensity level and the spin-down time to stop can be around 100 ms or more [Mortimer et al., 2007].

VBW32 tactor

The Tactaid VBW32 tactor is an inertial actuator that was specifically

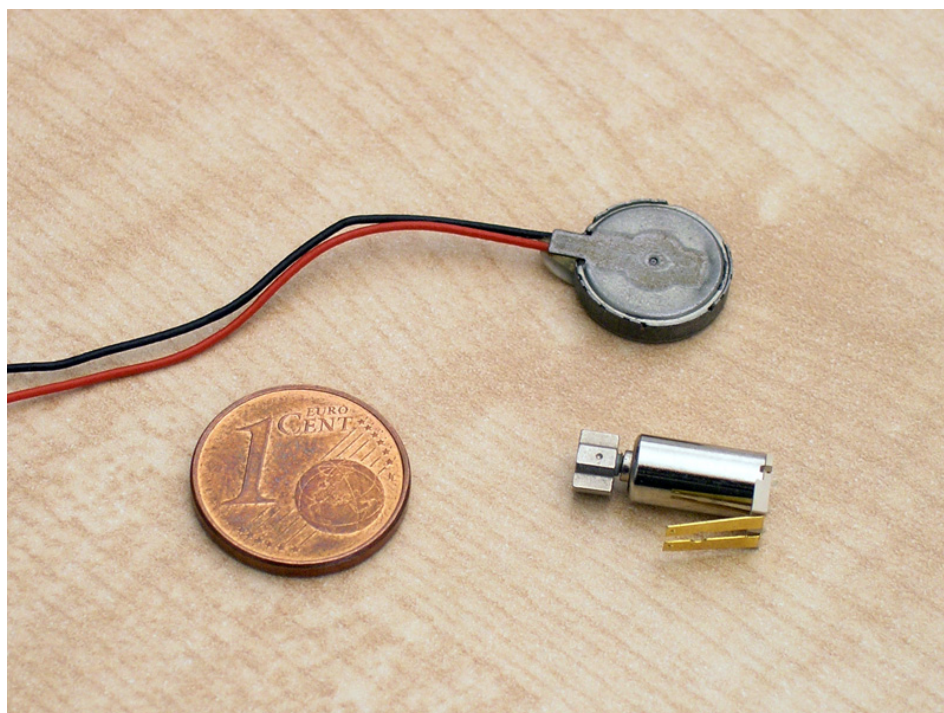


Figure 5.2: A pancake motor (top) and a cylindrical motor (bottom).

designed as a tactile hearing aid for hearing impaired persons [Audiologic Engineering Corporation (AEC), 1982]. In contrast to vibration motors, this tactor does not rotate a mass but uses a coil that attracts or repels a magnet when an alternating electromagnetic force is generated [Cholewiak and Wollowitz, 1992, Brown, 2007]. Its vibration frequency is around 250 Hz, and its response time is around 12.5 ms [Brown, 2007].

In contrast to inertial actuators, *linear actuators* do not shake the device. They typically consist of a voice-coil or solenoid (a loop of wire wrapped around a metallic core) that attracts a metal rod when voltage is turned on. A spring pulls the rod back to its original position when voltage is turned off. This sequence of opposing movements drives the rod perpendicularly to the skin. Since the moving rod spins neither up nor down, linear actuators have quick response times [Niwa et al., 2004, Mortimer et al., 2007].

Linear actuators move a rod perpendicular to the skin.

The C2 tactor (around 150 Euros) is such a linear actuator [Engineering Acoustics Inc., 2010]. The diameter of the rod that stimulates the skin is 0.7 cm. This rod produces a strong and localized sensation at the contact point, while the passive housing shields the surrounding skin from stimuli. This device was designed to optimally stimulate the Pacinian corpuscles but can also produce stimuli across a wide range of frequencies. It is driven by sine wave tone bursts, can evoke sensations that feel smooth or rough, and has a response time around 5 ms [Brown, 2007].

C2 tactor

Another type of actuators exploits the *piezoelectric effect* that occurs in non-conductive materials, such as in certain ceramics and crystals, includ-

Piezoelectric actuators

ing quartz. Piezoelectric materials generate a voltage in response to applied mechanical stress. This effect is reversible: an applied voltage deforms the material. A piezoelectric actuator is a thin rectangular plate that consists of two sandwiched layers of piezoelectric materials with opposing polarity. Depending on the applied voltage, one layer of the plate contracts while the other layer expands. The resulting motion bends the plate. If one end of the plate is fixed, the other end can move to stimulate the skin [Poupyrev et al., 2002]. Multiple plates arranged in an array can stretch the skin [Hayward and Cruz-Hernández, 2000]. These actuators can also create spatiotemporal effects by moving tiny rods [Summers et al., 2001].

Shape memory alloys

A recent approach to create tactile displays involves shape memory alloys. These alloys change their shape in response to temperature. In cold state, the alloy can be easily deformed. Upon heating above a threshold temperature, the alloy returns to its original form. Through resistive heating, this characteristic can be exploited to control the shape and movement of materials [Coelho and Maes, 2008], to stimulate the fingertips [Scheibe et al., 2007], or to build passive texture displays [Harrison and Hudson, 2009]. Even so, shape memory alloys could be inappropriate for directly stimulating the skin because they are actuated by heat [Harrison and Hudson, 2009]. Another disadvantage is their slow response speed.

5.3 Parameters for Tactile Information Transfer

Different tactile signals can represent different information.

The various tactile sensations that we can perceive could represent information. For example, a mobile phone that vibrates an inertial actuator in a trouser pocket could signal either a voice call or a text message. To differentiate between these two messages necessitates two distinct tactile sensations. In this section, we will describe parameters that could be varied to create different sensations, and we will present guidelines for designing artificial tactile messages.

General design guidelines

Some guidelines and recommendations are general and apply to all application scenarios: tactile messages should be self explaining and composed of well-known meaningful components; tactile displays should be unobtrusive and comfortable to wear for longer time periods; the same display should avoid tactile clutter and sensory overload through simultaneous or sequential presentation of multiple messages [van Erp, 2002].

Concrete design guidelines

Concrete guidelines refer to the available parameters for encoding tactile messages. This set of parameters comprises frequency, amplitude, waveform, location, duration, rhythm, and spatiotemporal patterns. Since the tactile sense has certain capabilities in perceiving and discriminating differences along these dimensions, some parameters are better suited than others for encoding information. The technology that stimulates the skin (see section 5.2) and the situation in which tactile stimuli are delivered also influence which parameters are appropriate for conveying information. In the following paragraphs, we will take a closer look at these parameters.

The skin can perceive frequencies up to 1.000 Hz [Sherrick and Craig, 1982], but the usable range does not exceed 400 Hz [Cholewiak and Wollowitz, 1992]. The Pacinian corpuscles are most sensitive to frequencies around 250 Hz [Cholewiak and Collins, 1991, Verrillo and Gescheider, 1992] (see Table 5.1). Humans can absolutely identify between three and five frequency levels and up to eight levels when these frequencies are delivered at different intensities [Sherrick, 1985]. Even so, frequency and intensity can affect each other. Changes in intensity can lead to perceived changes in frequency [Geldard, 1957, Rothenberg et al., 1977].

Humans can identify 3–5 frequency levels.

The perceived intensity of a stimulus primarily depends on its amplitude, which determines how much the skin is deformed. When intensity encodes information, the stimulus should be strong enough to be detected but not too strong to cause pain or discomfort [Craig and Sherrick, 1982]. Humans can differentiate between 15 intensity levels and can absolutely identify three to four levels [Geldard, 1960, Craig, 1972]. For message transfer, these levels should be widely separated between the minimum intensity that can be detected and the maximum intensity that is comfortable [Geldard, 1960].

Humans can identify 3–4 intensity levels.

The waveform of a stimulus describes the shape of the vibration wave. This shape determines how rough the stimulus feels. Sine waves feel smooth, whereas square waves feel rough and most intense [Gunther et al., 2002, van Erp, 2002]. Besides frequency, waveform is hard to discriminate and less suited for encoding information [Geldard, 1957]. Even so, three levels of roughness can be differentiated with the fingertips [Brown, 2007].

Humans can differentiate between 3 levels of roughness.

The accuracy in identifying the location of a stimulus depends on several factors. Anatomical reference points, such as wrist and elbow, can help to estimate the position and to identify the location of the stimulus [Cholewiak and Collins, 2003]. Also, actuators should slightly rest against the skin, otherwise the vibration could reach the bone structure. Since bones relay vibration, the user might not be able to locate the stimulus [Brewster and Brown, 2004]. Moreover, the two-point threshold has to be considered to ensure that stimuli from neighboring actuators are perceived at different locations (see section 5.1).

Factors that influence how well a stimulus can be located on the body

Geldard [1957] recommends using stimuli that last between 0.1 seconds and two seconds (see also [Geldard, 1960]). Durations outside this range are either too short or too long for communicating information in most situations. Trained users can differentiate between 25 durations within this range. While four to five levels can be absolutely identified, three levels are recommended for untrained users. The ability to detect pauses between two stimuli depends on the intensity and the length of these stimuli [Gescheider et al., 1974]. In general, pauses of 10 ms can be detected such that two sequential signals are not perceived as one signal.

Humans can absolutely differentiate between 4–5 levels of duration.

Rhythm is an important design parameter for *Earcons*, which are audio messages [Blattner et al., 1989]. Design guidelines for Earcons state that rhythm should be as different as possible [Brewster et al., 1995]. Based on these guidelines, Brown [2007] has shown that rhythm is also a suitable

Rhythmic patterns vary the duration and timing of signals.

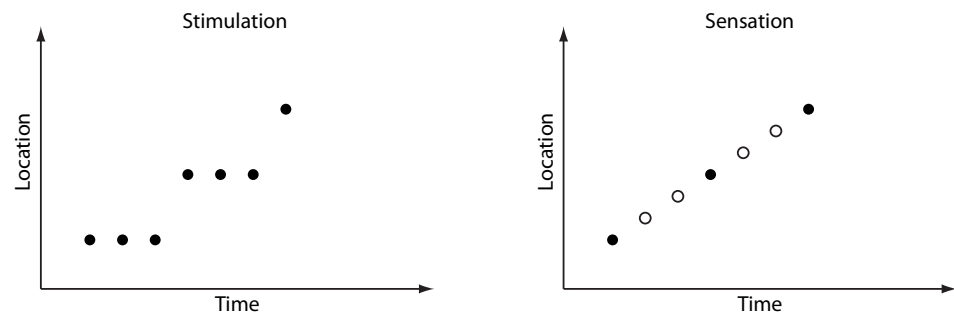


Figure 5.3: The sensory saltation phenomenon yields the impression that stimuli are delivered to locations between the mechanically stimulated points (adapted from [Tan and Pentland, 1997]).

parameter for tactile messages. These messages vary the duration and the timing of signals. When designing rhythmic patterns, the number of pulses that can be perceived within a given time is important. For example, we cannot accurately perceive if more than five pulses occur within 0.7 seconds [Sherrick and Craig, 1982].

Spatiotemporal patterns vary the location, duration, and timing of signals.

Spatiotemporal patterns resemble rhythmic patterns. They deliver signals closely in time and in space [van Erp, 2002]. When neighboring actuators are sequentially activated and deactivated, they produce the sensation of movement on the skin such that spatial patterns and directional lines can be drawn on the user's body [Brewster and Brown, 2004]. Two spatiotemporal effects are well known: apparent movement and sensory saltation.

Apparent movement

Apparent movement is the same as the visual phi phenomenon [Sherrick, 1968a, Craig and Sherrick, 1982]. When two neighboring light sources are sequentially activated for a short time, the light appears to move between these locations. The same effect exists when two neighboring tactile signals stimulate the skin. This effect also occurs if the signals stimulate opposing sites on the body, such as the left and right arm [Sherrick, 1968b].

Sensory saltation feels as if a tiny rabbit hops across the skin.

Sensory saltation evokes the illusion that tactile stimuli occur at locations where the skin was not mechanically stimulated [Geldard and Sherrick, 1972]. In the original experiment, three actuators placed in line at equal distance on the forearm sequentially delivered three pulses. Instead of perceiving individual pulses, phantom impressions equally distributed between the first and the last location were perceived. This sensation felt as if a tiny rabbit hopped across the skin [Geldard and Sherrick, 1972] (see Fig. 5.3).

Timing values for sensory saltation

To evoke sensory saltation necessitates at least two stimulation points with each two pulses [Geldard, 1975]. The illusion becomes more robust with up to six pulses per location [Geldard, 1985]. Larger numbers of taps can also evoke saltation unless the stimuli persist for too long under the same positions. The gaps between pulses can range from 20–300 ms. Pauses between 40–60 ms yield optimal results with vivid and regularly perceived hops [Geldard, 1985].

Sensory saltation can occur upwards, downwards, or simultaneously upwards and downwards at different body locations. An interesting characteristic of saltation is that this effect can be used for drawing directional lines. In particular, the direction of these lines can be identified without learning the meaning of these patterns in advance [Tan et al., 2000].

Saltation can be used for drawing directional lines

The aforementioned parameters are most often used for creating artificial tactile sensations. Some characteristics of the tactile sense, however, can change the intended perceptions. For example, the skin integrates stimuli that are delivered close in time and in space such that masking effects can occur [van Erp, 2002]. These effects can change the quality and the timing of the stimuli, which can make certain stimuli difficult to detect and to identify. Masking effects can be reduced when the stimuli vibrate at different frequencies or when the pauses and the distance between them increases. Also, the mechanoreceptors tend to adapt to a constant stimulus (see section 5.1). This adaptation can alter the perceived intensity and the intensity threshold for detecting a stimulus [van Erp, 2002].

Masking effects and adaptation can influence the tactile perception.

Overall, according to Geldard [1957], the three primary parameters for encoding tactile messages are amplitude, duration, and body location. He stated that “Certainly one can distinguish a strong from a weak burst of vibration, a long from a short one, and there is no difficulty in saying which arm or leg receives it.”. Brown [2007] suggested spatial location, duration, and rhythm, whereas intensity should be carefully considered because various factors can influence how users perceive magnitude.

Primary encoding parameters

Another issue that has to be considered is the encoding strategy for representing information as tactile messages. Craig and Sherrick [1982] differentiated between the *pictorial* approach and the *coded* approach. The pictorial approach directly transfers information from one sense to another sense (Brown [2007] named this the *direct* approach). For example, the Optacon reading device rendered the shape of a scanned image onto the fingertips such that the meaning of the stimuli was self-explaining (see section 5.4.1). In contrast, the coded approach uses an abstract mapping between a stimulus and its meaning such that this relationship has to be learned. Even so, coded messages can represent any information, including data that does not have a pictorial representation.

Encoding strategies: the pictorial and the coded approach

One examples of coded messages are *Haptic phonemes* [MacLean and Enriquez, 2003], which are constructed of simple waveforms. These short abstract signals could represent information on the state, function, or content of objects and events, which are called *haptic icons* (hapticons).

Haptic icons

Another example are *Tactons* [Brewster and Brown, 2004], which are based on the structure and design principles of Earcons [Blattner et al., 1989]. Tactons (tactile icons) are rhythmic or melodic patterns that could provide feedback in user interfaces. Brewster and Brown [2004] differentiate between one-element, compound, inherited, and transformational Tactons.

Tactons are structured messages that encode multi-dimensional information.

One-element Tactons are short bursts or temporal patterns. *Compound*

Tactons are a sequence of two or more one-element Tactons. *Inherited* Tactons are hierarchically combined. For example, while the Tacton at the highest level has a certain rhythm, a Tacton at the next level preserves this rhythmic structure but ends with a higher frequency Tacton rendered with a different waveform. Lower level Tactons then change the tempo or another parameter. *Transformational* Tactons represent the properties of the delivered messages as different tactile parameters. For example, to represent files in a computer interface, rhythm could encode the type, frequency the size, and body location the creation date. Brown [2007] presented guidelines for designing Tactons and showed that users could learn and identify these abstract messages.

The metaphorical approach

Another encoding strategy is the *metaphorical* approach [Brown, 2007], which relies on common and known metaphors, such as a heartbeat [Chan et al., 2005]. Heartbeat and hug-like sensations could convey personal and emotional information over distance (see section 5.4.5). Other encoding strategies relate to semiotics and exploit the meaning and interpretation that people assign to touch [Brown, 2007].

5.4 Applications for Tactile Feedback

Artificial tactile messages are usually applied in situations when the visual or auditory sense cannot process information or when these senses are overloaded. Since the 1960s, several devices have been built for assisting blind, visually impaired, or hearing impaired persons. During the last 20 years, various other scenarios have been explored. In this section, we will give an overview of the most common applications, based on the aforementioned tactile display technologies and parameters for tactile information transfer.

5.4.1 Sensory Substitution

Reading aids for blind and visually impaired persons.

Sensory substitution systems substitute visual or sound information with tactile signals [Kaczmarek et al., 1991]. The *Braille* alphabet, devised in 1821 by Louis Braille, a blind person, is such a system. Braille presents textual information to the fingertips. Rectangles of raised and lowered dots encode characters, numerals, and punctuation (see Fig. 5.4, left). Experienced adults can reach reading speeds of over 100 words per minute [Schiff and Foulke, 1982]. One discontinued device that rendered Braille symbols was the VirTouch tactile mouse. This mouse had three arrays of pins that displayed spatial and temporal patterns for assisting users in reading text, and in recognizing pictures and graphics [Wall and Brewster, 2006].

The Optacon device for reading text displayed images as vibration

The Optacon reading device converted visual information into tactile cues (see Figure 5.4, right). The user placed the finger on a tactile array that consisted of metal rods. By moving a small camera over text, the rods that corresponded to black parts of the captured image vibrated. This vibration

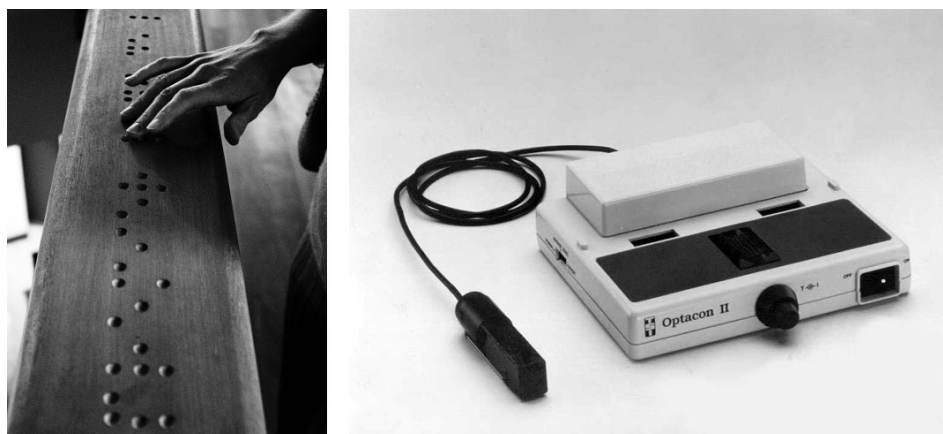


Figure 5.4: Left: The Braille alphabet uses a sequence of dots that can be read by touch (photo by Christophe Moustier, Wikimedia Commons). Right: The Optacon II reading device displayed on its tactile array the spatial pattern of the captured image (source: Wikimedia Commons).

displayed the spatial pattern of the text. Experienced users reached reading speeds between 30–50 words per minute [Craig and Sherrick, 1982].

A different approach for conveying textual information as cutaneous patterns mapped letters and numbers to tactile signals of different intensities, durations, and body locations. The *Vibratese* language presented these signals with an array of nine actuators located at the chest [Geldard, 1957]. The *Optohapt* system used nine actuators distributed across the whole body [Geldard, 1966]. Experiments showed that people could learn and read the developed tactile languages (see also section 7.1).

Tactile languages
for reading text

Other sensory substitution systems supported hearing impaired persons. For example, Tactaid devices with VBW32 tactors (see section 5.2) could convert environmental sound information into unique vibration patterns [Audiologic Engineering Corporation (AEC), 1982]. As these devices could reveal sound differences such as between voiced and unvoiced consonants, they were used for supporting children during speech training [Weisenberger and Percy, 1994].

Aids for the deaf
and hard of
hearing

5.4.2 Navigation Systems

Navigation towards waypoints is a popular scenario for tactile feedback. A wearable computer that tracks the user's location with the Global Positioning System (GPS, see gps.gov) could provide localized tactile pulses that indicate the direction to walk. Ross and Blasch [2000] tested such an interface with visually impaired persons. Their shoulder-tapping system consisted of three actuators located at the back. The center actuator was activated when the walking direction was correct, whereas the left and right actuators signaled the new direction to walk when the user was off target.

Navigation
towards targets

Compared to spoken instructions and other audio cues, these tactile signals yielded better performance and were preferred by users. Directional lines based on sensory saltation could also convey guidance signals [Tan and Pentland, 1997]. For example, Ertan et al. [1998] and Jones et al. [2006] reported that trained users were able to recognize with almost perfect accuracy directional lines that were delivered to the back while walking.

Navigation with a waist belt

Several other systems are based on the same idea. For example, Tsukada and Yasumura [2004] built a waist belt with eight actuators for pedestrian navigation. The location of vibration around the waist signaled the direction to walk, whereas the pulse intervals indicated the distance to the target, using shorter intervals when the user approached the destination. A similar waist belt for waypoint navigation was tested with helicopter pilots and boat navigators [van Erp et al., 2005]. For automobile drivers, *Vibrocons* were introduced as tactile navigation symbols [van Erp and van Veen, 2001]. Actuators under the left or right leg indicated a left or right turn, whereas consecutive activation of all actuators under both legs from back to front signaled to go straight.

Improving spatial awareness in aviation

Another scenario for tactile feedback is aviation. Jet pilots could lose their orientation when high forces act on their bodies during flights. To resolve such mishaps, Rupert [2000] proposed a tactile situation awareness system. The pilot could wear a suit consisting of an array of actuators arranged in columns and rows. To indicate the orientation of the plane, this array could deliver tactile stimuli to the torso that represent roll and pitch angles. For example, to encode the direction of the gravity vector in 3D space with respect to the pilot's position in the seat, a stimulus at the lower left side of the torso could indicate a slight tilt of the aircraft to the left. Actuators located higher at the left side could signal an increased tilt of the aircraft. These stimuli could also support pilots when visually scanning instruments. The same approach could help astronauts to experience the orientation of a space ship [van Erp and van Veen, 2003].

5.4.3 Warning Signals

Warning signals alert pilots to critical events.

When visual attention is vital, such as during flights, tactile warning signals could direct the attention towards critical events. Sklar and Sarter [1999] reported that tactile cues applied to the wrist could direct a pilot's attention to unexpected events and status changes that occurred in automated cockpit systems. Moreover, these warning signals increased the detection rates of automatic mode changes and decreased the pilot's response times compared to the standard situation when the pilot visually scanned the instruments.

Warning signals for car drivers

Also, a tactile stimulus at the accelerator pedal could indicate if a car driver exceeded the allowed speed limit [van Winsum, 1999]. This stimulus increased the driver's performance and reduced the workload compared to

an audio message. Tactile signals at the back could also direct a driver's attention to the back mirror [Ho et al., 2005]. These signals decreased the driver's response time and increased the accuracy in responding to time-critical events, such as when a car rapidly approached from behind.

Besides guiding visually impaired persons towards a destination, tactile signals could warn of obstacles. For example, Cardin et al. [2006a] built a system that could spot nearby objects in the walking path with ultrasonic transducers attached to the body. Actuators at the waist indicated the location and the distance to these objects. The haptic radar [Cassinelli et al., 2006] was a similar warning system, based on infrared proximity sensors that could detect objects in the environment. To warn workers of unseen objects that might approach from behind during safety-critical tasks, actuators in the safety hat could deliver warning signals to the head.

Obstacle
detection

5.4.4 Interaction with Mobile Devices

Compared to audio messages, tactile messages are discreet. They do not disturb nearby users, neither do they compromise private information [Chang et al., 2002]. Even so, mobile phones seldom make use of such messages. In general, they only pulse a vibration motor to announce incoming calls and text messages, or to signal low battery status.

Tactile messages
are private but
underused.

A simple tactile signal, however, could significantly improve the interaction with mobile user interfaces. For example, during a text scrolling task that required tilting the device, a pulse that indicated when a line of text scrolled up or down reduced the task completion time compared to scrolling without tactile feedback [Poupyrev et al., 2002]. Other scenarios involved list selection, status notifications, and navigation towards destinations [Luk et al., 2006]. Moreover, Williamson et al. [2007] described a simple technique for actively sensing data in mobile phones. Upon shaking the device, virtual message balls were simulated that bounced around. These balls expressed certain impact characteristics that revealed the properties of unread messages: impacts that felt deep and heavy indicated long text messages, whereas impacts that felt lighter indicated several short messages.

Improved
interaction with
handheld devices

Tactile feedback has also been shown to decrease typing errors and to increase typing speed on touchscreen devices [Hoggan et al., 2008]. Moreover, force-feedback could reduce typing errors on physical keyboards, using software that analyzed the typed words and that dynamically adjusted the pressure resistance of keys through solenoids [Hoffmann et al., 2009]. Before each keystroke, the resistance of keys that would have lead to a typing error according to dictionary and grammar rules was increased such that the user could notice possible typing errors in advance.

Tactile feedback
decreases typing
errors.

5.4.5 Distant and Emotional Communication

Tactile stimuli can represent feelings.

People often touch each other when they talk. Intimate gestures, such as a handshake, a hug, or a kiss express feelings. To promote a sense of awareness between distant people, tactile displays could simulate such gestures. For example, inTouch [Brave and Dahley, 1997] and HandJive [Fogg et al., 1998] are shared physical objects that could connect spatially separated users. While each user interacts with the personal object, this interaction would affect the distant object and would convey remote presence. Com-Touch [Chang et al., 2002] could augment audio communication over mobile phones in a similar way. Each device includes sensors for measuring forces applied by the fingers and actuators for creating tactile stimuli. When users grasps and squeeze their devices during conversation, the remote partner could immediately perceive this tactile interaction, which could emphasize a specific phrase, indicate turn-taking, and signal attention or nodding.

Hugging over a distance

The Hug Shirt [CuteCircuit, 2010] is a similar system that could promote distant awareness between friends and that could send hugs over a distance [Mueller et al., 2005]. This shirt contains pads with built-in sensors and actuators located at those body areas that people usually touch when they hug, such as the upper arms, the shoulders, and the back. When these pads are touched, the sensors measure the applied pressure, the skin temperature, and the heart beat. This data is transmitted over the mobile phone to the remote partner, whose Hug Shirt would recreate the sensation of touch, warmth, and emotion.

Benali-Khoudja et al. [2005] and Salminen et al. [2008] investigated how tactile patterns delivered to the fingertips were perceived and interpreted. They found that certain characteristics of tactile stimuli, such as their direction and continuity, could represent emotional information, including affection, pleasantness, and arousal. Such stimuli could enrich the interaction in virtual reality and telepresence applications. Also, they could enrich text messages in instant messaging applications, which lack non-verbal communication cues [Rovers and van Essen, 2004].

Enhancing music performances

Moreover, tactile signals could accompany music performances [Gunther et al., 2002]. Similar to perceiving low frequency vibrations when standing close to powerful speakers, multiple actuators placed across the body could intensify and enhance the listeners' feelings and experience.

5.4.6 Virtual Reality

Interaction in virtual environments

Virtual reality simulates three-dimensional environments with head-mounted and CAVE-like displays [Cruz-Neira et al., 1992]. Since the user cannot touch virtual objects, tactile and force feedback devices could make the interaction in these environments feel realistic. For example, actuators could render localized stimuli that indicate when the body collides with walls or with objects [Yano et al., 1998, Lindeman et al., 2004a, Schätzle

et al., 2006] (see Fig. 2.3 for the TactaVest). The CyberTouch tactile feedback system for the CyberGlove [CyberGlove Systems, 2007] can stimulate the fingers and the palm with small vibrotactile actuators when the user touches solid virtual objects. This glove has also been used for remote exploring of objects in teleoperation applications [Aleotti et al., 2002]. Another approach for simulating contact with virtual objects used thimbles with contractible wires around the fingertips [Scheibe et al., 2007] (see shape memory alloys in section 5.2). Also, force feedback devices were used for surgical training [Chen and Marcus, 1998], for remote controlling of robotic vehicles [Stone, 2001], and as controllers for computer games.

5.5 Closing Remarks

Researchers have explored various applications for artificial tactile stimuli, and they have shown that these stimuli could effectively convey information to users. Our goal was to apply tactile stimuli as messages that signaled how to move the body during physical activities. Therefore, in this chapter, we have first discussed how the skin processes tactile stimuli and which sensations humans can perceive. Then, we have reviewed parameters for encoding information as tactile signals, and we have presented technologies and example applications that conveyed messages over the tactile sense.

In the next chapter, we will introduce tactile motion instructions, and we will describe the design and evaluation of full-body tactile patterns that could represent body movements in an intuitive way.

Chapter 6

Tactile Motion Instructions

“I never teach my pupils. I only attempt to provide the conditions in which they can learn.”

—*Albert Einstein*

In this chapter, we will explore artificial tactile stimuli as instructions how to move the body during physical activities. We call these stimuli *tactile motion instructions*. The idea behind tactile motion instructions is simple: stimuli that affect the skin can trigger body movements. For example, we are likely to turn around when we unexpectedly feel a tap at the shoulder. Moreover, the location of the tap can influence our movements. A tap at the left shoulder makes us turn to the left, whereas a tap at the right shoulder makes us turn to the right. This example illustrates that we habitually respond to tactile stimuli by moving the body in a certain direction.

Tactile stimuli can result in reflex actions.

We believe that artificial tactile stimuli can intuitively represent body movements and that they can instruct athletes how to move. This idea relates to tactile navigation displays that signal the direction in which to walk (see section 5.4.2). Van Erp et al. [2006] proposed a similar idea for sports training and mentioned that a vibrating element could replace the hand of the coach in dynamic situations when coaches cannot physically push and pull a student’s limb into the desired position. They differentiated between three applications: where to move to, how to move, and when to move.

Applications of tactile feedback systems in sports

Where to move to: People directly map a tactile stimulus to body coordinates [van Erp, 2005]: a stimulus on the left side of the body represents left; a stimulus on the right side of the body represents right; a stimulus on the front or on the back of the body represents front or back. Since such localized stimuli can intuitively represent spatial direction, they can indicate the direction towards a target relative to the position of the body. Besides navigation [Ross and Blasch, 2000, van Erp and van Veen, 2001, Tsukada and Yasumura, 2004, van Erp et al., 2005] (see section 5.4.2), such stimuli could be applied to sports training. For example, they could signal team players in which direction to look and move [Van Erp et al., 2006].

A localized tactile stimulus could signal the direction where to move.

A stimulus could signal when to initiate a movement.

When to move: The onset of a tactile stimulus could signal the time when to move. Timing information is in particular important for sequences of body movements. For example, oarsmen have to precisely time their leg and back movements to achieve optimal performance. In this case, localized stimuli delivered to the back and to the knees could indicate when to move the back and when to move the knees [Van Erp et al., 2006].

A stimulus could signal how to move the body.

How to move: A tactile stimulus could indicate how to move the limbs and the body. For example, to optimize the posture of the back in speed skating and cycling, a stimulus could signal to lower the shoulders [Van Erp et al., 2006]. Other works proposed stimuli for indicating deviations from allowed movements, thereby guiding wrong movements back to the desired movement path [Lindeman et al., 2006a, Lieberman and Breazeal, 2007].

We have focused on tactile stimuli that could signal how to move the body.

These applications for artificial tactile stimuli are not limited to sports where coaches cannot immediately provide feedback on the posture and on the timing of body movements, such as in the aforementioned examples or in snowboarding, skiing, and surfing. In fact, they could guide athletes to the correct movements in any sport, including martial arts, dancing, and ballet. In addition, they could support people or patients in correcting wrong posture in unsupervised situations, for example while gardening or during rehabilitative exercises at home. The variety of physical activities that could benefit from tactile instructions inspired us to investigate which tactile stimuli could be applied as instructions. In particular, our goal was to find tactile stimuli that could intuitively represent body movements, similar to the tap at the shoulder that could make us to turn around.

This is the first investigation into tactile instructions for physical activities.

Until now, however, it has not been investigated which artificial tactile stimuli can intuitively represent body movements, nor have they been examined in detail in the context of sports training and daily physical activities. Since physical activities are by their nature physically and often cognitively demanding, they might degrade the ability of people to perceive these stimuli. For example, athletes experience exhaustion, pain, and muscle strains, whereas clothes create friction on the body. Moreover, athletes focus their attention on the sport because they have to quickly adjust their movements and posture to changing situations. This raises the question which tactile stimuli are appropriate as instructions in active situations.

This dissertation provides the first investigation into artificial tactile stimuli that can convey instructions how to move the body during physical activities. A part of this work was done by Jacobs [2008] and Hilgers [2008] under the guidance of the author. In particular, we have investigated

- how young adults intuitively responded to tactile stimuli delivered across the body and which body movements they performed,
- how well young adults perceived and recognized tactile instructions in active situations that were physically and cognitively demanding,
- how tactile instructions compared with spoken instructions delivered over earplugs,

- if tactile instructions establish a tactile language (see chapter 7),
- if tactile instructions could enhance the performance and learning of motor skills (see chapter 8).

The remaining of this chapter is organized as follows:

- Section 6.1 discusses requirements on tactile motion instructions and introduces a formal notation for documenting artificial tactile stimuli.
- Section 6.2 presents an exploratory study on the intuitive interpretation of artificial tactile stimuli delivered across the body.
- Section 6.3 and section 6.4 report on the design, perception, and interpretation of a first set of tactile motion instructions that were evaluated with young adults in stationary and in active situations.
- Section 6.5 lists a first set of guidelines for designing tactile motion instruction patterns and presents ten tactile instructions that evolved from our investigation.

6.1 Informing the Design

The design space of mobile tactile interfaces can be organized along two dimensions [Poupyrev et al., 2002]. One dimension specifies the amount of cognitive load that the device imposes on the user. This dimension denotes how much conscious attention the user has to spend at the expense of other tasks. The other dimension denotes how abstract the representation of the conveyed information is (see Fig. 6.1).

An abstract representation does not have a direct relationship between the tactile stimulus and the conveyed message. Such a message is based on the coded approach (see section 5.3). Coded messages can represent any information, but they can increase the amount of cognitive load that is required for perceiving and interpreting the stimulus. Examples of abstract messages that do not require a high amount of cognitive load include Ambient Touch events for handheld devices [Poupyrev et al., 2002], such as a tactile notification that could represent an incoming message. If, however, different tactile notifications were used for representing the type of the message, which could be represented as Tactons [Brewster and Brown, 2004] or as haptic icons [MacLean and Enriquez, 2003] (see section 5.3), the amount of cognitive load required for recognizing the message type would increase. High cognitive load is also required for understanding the tactile language Vibratese [Geldard, 1957] (see section 5.4.1) or for precise blind control when the user can only operate a device through touch.

We are interested in tactile stimuli that can be perceived and interpreted with a minimum amount of cognitive load in active situations. In particular,

The design space of mobile tactile interfaces

Abstract tactile stimuli can increase the amount of cognitive load required for interpreting the conveyed message.

Real-world sensations

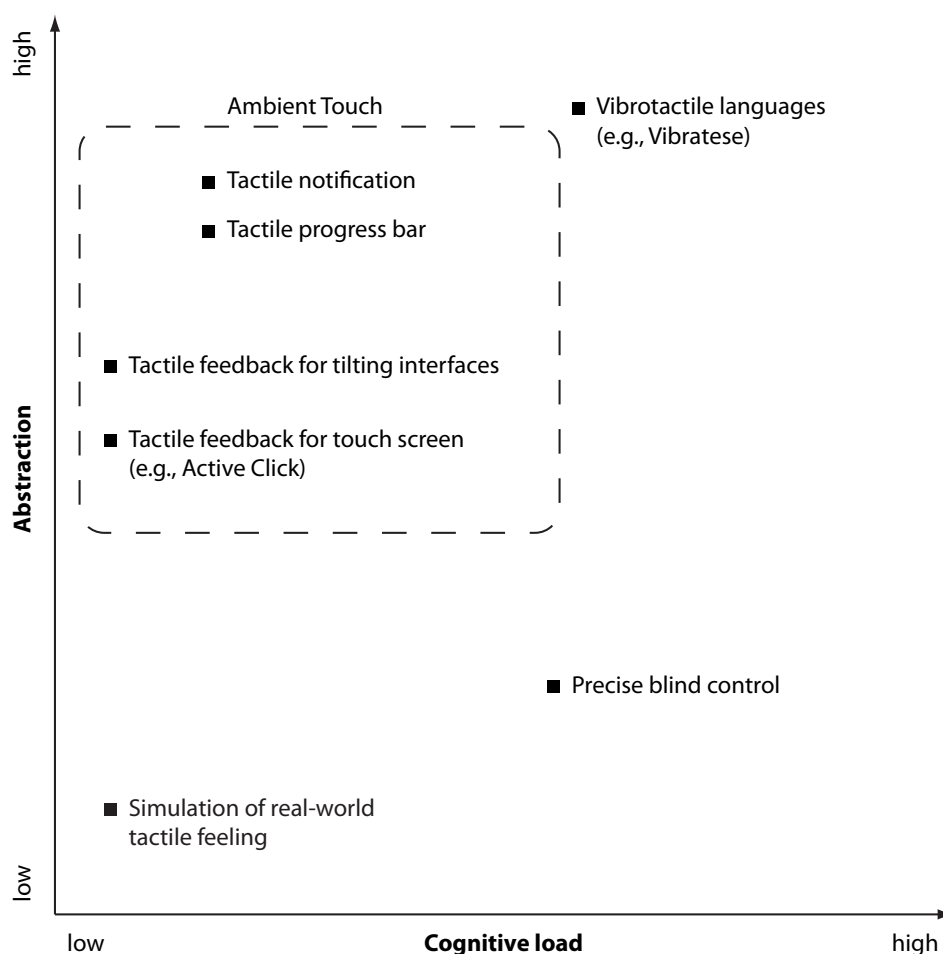


Figure 6.1: The design space of mobile tactile interfaces (adapted from [Poupyrev et al., 2002]).

tactile motion instructions should ideally resemble expressive real-world sensations, such as pushing and pulling sensations that are unambiguous. Tactile displays that evoke such sensations on the body do not yet exist. This leaves localized tactile stimuli as basic building blocks for simulating sensations that feel realistic. In the following sections, we will discuss our approach to designing tactile motion instructions based on these stimuli.

6.1.1 Expressive Sensations

Localized stimuli have been applied as instructions and notifications.

We have noted before that we are likely to turn around when we perceive a tap at the shoulder, in particular if we expect that a person touches us. Artificial tactile stimuli, which resembled such a tap, have already been applied to navigation for signaling in which direction to walk (see section 5.4.2) and for signaling when users collided with or touched virtual objects (see section 5.4.6). These examples illustrate that a simple localized stimulus, such as a pulse, can be effectively applied to the body as an instruction or a notification that represents an event in a particular context.

We have focused on physical activities. If we used a pulse in this context, this pulse could represent a body movement. For example, a stimulus at the right arm could indicate to raise the right arm. A stimulus at the right wrist could represent a punch with the right fist. Likewise, a stimulus at the lower left leg could represent a dance step or a kick with the left leg, whereas stimuli at both thighs could represent flexing or stretching the legs.

A pulse could represent a body movement.

Even so, a pulse is abstract. Since a pulse does not inherently describe how to move the body or the limb that was stimulated, the user would have to learn the mapping between this stimulus and the meaning that it could represent. Consequently, the amount of cognitive load required to recall the meaning of this inexpressive stimulus would increase.

A simple pulse is inexpressive and requires to learn its meaning.

Moreover, the location where the pulse is applied to the body could influence how intuitive the user considers the mapping between the stimulus and its meaning, and how fast the user responds. For example, Jansen et al. [2004] reported that a pulse that was applied for 200 ms laterally to the side of the hand in order to indicate the direction in which to rotate the hand (*extrinsic frame of reference*) resulted in faster reaction times than a pulse that was delivered laterally to the forearm, which stimulated the muscles that contracted when the hand was rotated (*intrinsic frame of reference*). Lateral stimuli, however, would be better suited for indicating a translation of the hand to the left or right than a rotation [Jansen et al., 2004].

The location of a stimulus could influence how intuitive the user considers the conveyed message and how fast the user responds.

Instead of a simple pulse, a directional line based on sensory saltation evoked across a larger body area could result in an expressive sensation that could be self-explaining as an instruction how to move the body. For example, Tan et al. [2000] reported that untrained users could identify the direction of sensory saltation at the back (see section 5.3). Moreover, such directional lines were effectively applied to the back in order to signal the direction to walk [Ertan et al., 1998, Jones et al., 2006]. Also, a series of signals delivered across multiple actuators could indicate rotation [Gemperle et al., 2001], such as around the wrist for signaling the direction in which to rotate the hand [Lieberman and Breazeal, 2007]. If we expand on this idea, rotation around the waist could indicate to turn left or right, and directional lines at the thighs in upward or downward direction could signal to stretch or to flex the legs.

Directional lines could create expressive sensations.

The intensity and the spatial dimension of tactile stimuli could also help design expressive sensations. For example, an intense sensation perceived across a large body area could represent a wide and a fast movement, similar to a strong push through the coach's hands.

Stimulus intensity and spatial dimension

6.1.2 Stimulus Duration and Perception under Workload

Another important issue for designing tactile instructions is the duration of the applied stimuli. A tactile instruction should be long enough to be perceived but short enough to be quickly interpreted such that the user

Guidelines on the duration of tactile stimuli

can quickly react. Guidelines on the minimum duration of tactile messages suggest a stimulus of 100 ms [Geldard, 1957]. For directional lines based on sensory saltation, three pulses per actuator were commonly applied [Geldard, 1975, Cholewiak and Collins, 2000, Tan et al., 2003]. In this case, pulse durations of 20-300 ms and pauses of 40-60 ms evoked optimal sensations [Geldard, 1985]. These timing values, however, were derived from a stationary situation and might not apply to active situations.

Cognitive workload can degrade the ability to locate brief tactile stimuli.

Related work provides a few hints on the timing values for tactile stimuli that could be perceived in active situations, including findings of studies that investigated how well young adults could identify the location of vibrotactile pulses under cognitive workload. For example, young adults who floated in an airplane during parabolic flights had difficulty in identifying the location of a pulse of 250 ms duration applied to the torso [Bhargava et al., 2005] and in identifying the direction of sensory saltation applied to the back [Traylor and Tan, 2002]. This physical activity obviously required the participants to pay attention to floating in zero gravity and to avoid bumping into objects, which distracted them from paying attention to the pulses [Traylor and Tan, 2002, Bhargava et al., 2005]. Even so, the authors noted that the effect of cognitive load on the ability to pay attention to the pulses might decrease as one becomes accustomed to the physical task.

The location of long pulses and of short sequences of pulses could be identified under cognitive workload.

The findings of other studies indicate that participants who were involved in tasks that required cognitive workload could perceive and identify the location of a long pulse or of a sequence of short pulses. For example, middle-aged men were able to identify to which side of the torso pulses of 100 ms duration followed by 200 ms pauses were applied while sitting in a centrifuge, which simulated high G-load conditions that jet pilots experienced [van Veen and van Erp, 2001]. Also, the location of a 1000 ms pulse that was applied to different locations around the waist was identified while navigating a helicopter and a fast boat [van Erp et al., 2005].

Tactile signals were perceived during tasks performed in flight and driving simulators.

Other studies also indicate that participants were able to perceive and to identify tactile warning and navigation signals applied to the wrist and to the torso during flight simulator and driving simulator tasks: a 200 ms pulse [Cardin et al., 2006b]; a 500 ms pulse [Sklar and Sarter, 1999]; a 1060 ms pulse [Ho et al., 2005]; and sequential pulses of 60 ms with varying pauses [van Erp and van Veen, 2001]. Also, the location of vibration applied to the left or to the right arm could be identified while running through a military obstacle course, but no details on the nature of these stimuli was reported [Lindeman et al., 2004b].

We chose three pulses as basic stimulus for composing tactile patterns.

Overall, the aforementioned findings on the perception of tactile stimuli in active situations suggest using pulse durations around 250 ms or a sequence of briefer pulses. For these reasons, we have decided to apply three localized pulses as basic pattern for simulating a tap, based on a *burst duration* (BD) of 100 ms and an *inter-burst interval* (IBI) of 50 ms (IBI denotes the pause between two bursts). Fig. 6.2 illustrates these timing values for a tap and for a directional line.

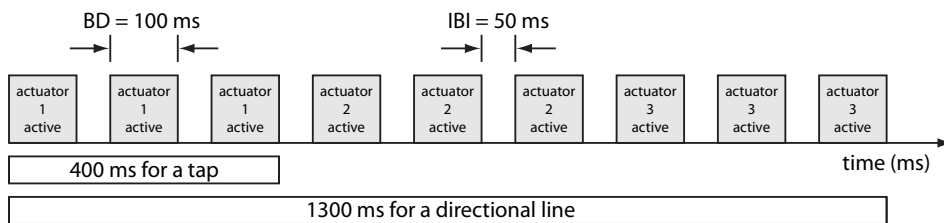


Figure 6.2: The timing values for tactile stimuli as investigated in this work. For directional lines that evoked sensory saltation, the three actuators were positioned at different locations in line, as illustrated in Fig. 5.3.

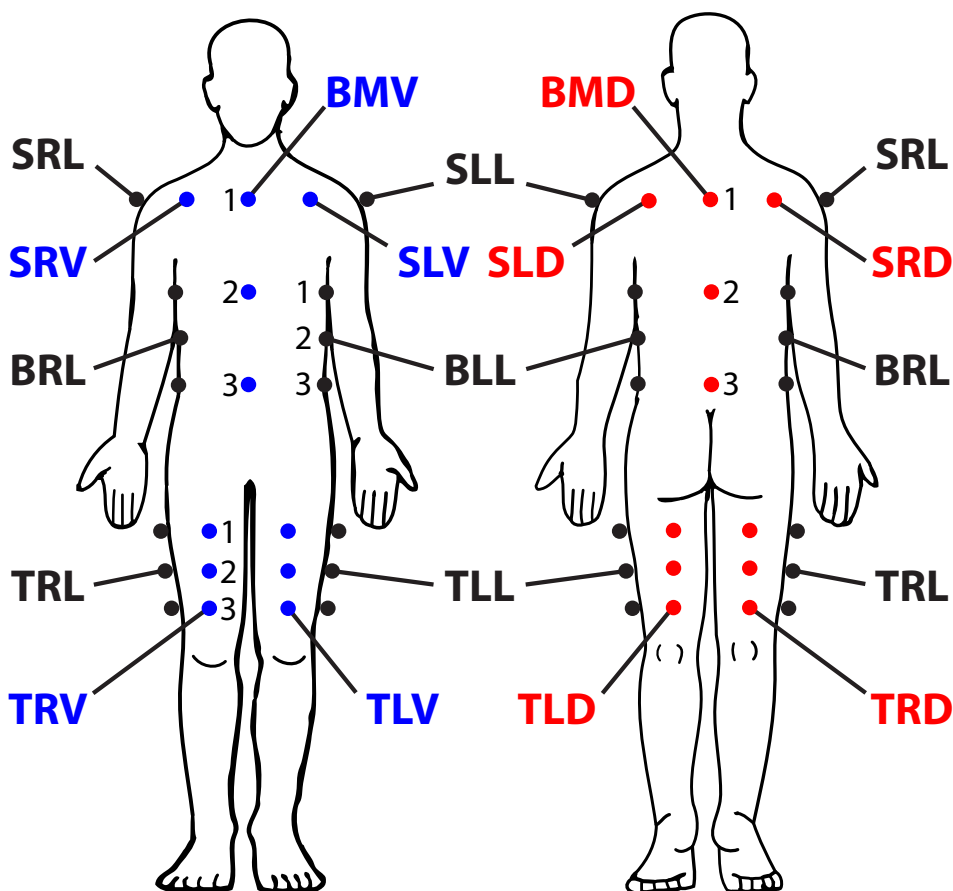


Figure 6.3: The stimulated body areas for finding tactile motion instructions. The dots represent the position of actuators as investigated in this work. Table 6.1 summarizes acronyms that identify these positions.

6.1.3 Stimulus Locations on the Body

The area of the skin that could receive tactile instructions is large. To cut down the search space for finding promising locations, we chose body areas that seemed appropriate for receiving the aforementioned localized pulses and directional lines (see Fig. 6.2). Fig. 6.3 illustrates these areas, which comprised the shoulders, the torso, and the thighs (front, back, and lat-

We focused on body locations that seemed appropriate for pulses and for directional lines.

Table 6.1: Three-letter acronyms denote the position of actuators: first letter = body location; second letter = left/right/medial; third letter = ventral/dorsal/lateral (medial = middle, ventral = front, dorsal = back).

| Acronym | Body location | Acronym | Body location |
|---------|-----------------------|---------|------------------------|
| SLL | Shoulder Left Lateral | SRL | Shoulder Right Lateral |
| SLV | Shoulder Left Ventral | SRV | Shoulder Right Ventral |
| SLD | Shoulder Left Dorsal | SRD | Shoulder Right Dorsal |
| BLL | Body Left Lateral | BRL | Body Right Lateral |
| BMV | Body Medial Ventral | BMD | Body Medial Dorsal |
| TLL | Thigh Left Lateral | TRL | Thigh Right Lateral |
| TLV | Thigh Left Ventral | TRV | Thigh Right Ventral |
| TLD | Thigh Left Dorsal | TRD | Thigh Right Dorsal |

eral). Since the spatial acuity of the skin varies on the body, we considered the two-point threshold for determining the minimum distance between neighboring stimulation points (see section 5.1). We omitted the calves, which might be inappropriate for tactile stimuli while wearing shoes, and the arms, which might be moved to different positions in active situations.

6.1.4 A Notation for Tactile Patterns

A formal notation captures the structure and the characteristics of tactile stimuli.

Related work described and documented tactile stimuli textually and visually. For example, sequences of numbers, such as 111222333, were used to specify the temporal order in which to activate actuators [Tan et al., 2003], and arrows represented the spatial order of activation [Jones et al., 2006]. Although these illustrations could visually describe the evoked sensations, they did not capture all characteristics of the stimuli. For this reason, we have introduced a formal notation for documenting the structure and properties of tactile stimuli that could represent tactile motion instructions.

Three pattern categories

Moreover, this notation can capture the fundamental characteristics of any tactile stimuli and can document three pattern categories: *one-element patterns*, *compound patterns*, and *simultaneous patterns*. These categories partly base on design principles introduced for Earcons [Blattner et al., 1989] and Tactons [Brewster and Brown, 2004].

One-element patterns

A one-element pattern will represent a single vibration burst or a temporal pattern. We will use $P(l)$ to denote a single pulse applied to the body location l . $P(l_x)$ will identify one specific actuator at this position. $P^3(l_x) = P(l_x) \rightarrow P(l_x) \rightarrow P(l_x)$ will represent three sequential pulses delivered by the same actuator.

Pulse characteristics

Pulses could have different characteristics. For example, they could vary the burst duration or the duration of pauses between sequential bursts. We will specify these characteristics as additional arguments. $P(l, d, p)$ will denote a pulse at location l with BD = d and IBI = p (in ms) (see Fig. 6.2).

$P(l_x, d1, p1) \rightarrow P(l_x, d2, p2) \rightarrow P(l_x, d3)$ will describe a pattern that varies the duration of the bursts and the pauses. For example, $P(SRL, 100)$ would laterally stimulate the right shoulder with a pulse of 100 ms, and $P^3(TRV_3, 100, 50)$ would sequentially deliver three pulses with actuator 3 located at the front of the right thigh, using pauses of 50 ms (see Fig. 6.3).

A compound pattern will display one-element patterns in succession. We will use $P(l_x) \rightarrow P(l_y)$ to denote pulses that sequentially stimulate different body locations. For example, $P^3(TRV_3) \rightarrow P^3(TRV_2) \rightarrow P^3(TRV_1)$ would sequentially pulse three actuators for three times to render a directional line in upward direction at the front of the right thigh (see Fig. 6.3). As a shorthand, we will use the symbol R (“rabbit”) to refer to sensory saltation. R_U and R_D will denote saltation in upward and downward direction. For example, the compound pattern $R_U(TRL) \rightarrow R_D(TLL)$ would start in upward direction laterally at the right thigh and would conclude in downward direction laterally at the left thigh.

A compound pattern is a sequence of one-element patterns

To repeat a pattern, a number $n \cdot (...)$ will specify how often the pattern will be sequentially applied. For example, $2 \cdot (R_U(TRL) \rightarrow R_D(TLL))$ would evoke saltation in upward direction laterally at the right thigh and saltation in downward direction laterally at the left thigh twice (see Fig. 6.3).

Repeated patterns

A simultaneous pattern will describe stimuli delivered to multiple body locations at the same time. We will use $P(l_x) + P(l_y) + P(l_z)$ to denote pulses that simultaneously stimulate different locations. For example, $P(SLD) + P(SRD)$ would stimulate the shoulder blades with a single pulse, and $R_U(TRV) + R_U(TLV)$ would simultaneously elicit saltation in upward direction at the front of both thighs (see Fig. 6.3). These patterns could be used for creating intense and large sensations.

Simultaneous patterns stimulate different body locations at the same time

Certain properties of tactile stimuli could be specified in advance and omitted for subsequent stimuli. For example, when the body location l has been named, P_x will be a shorthand for identifying actuator x at the given position. P_x^3 will denote three pulses applied to the same location, whereas $P_x^3 \rightarrow P_y^3 \rightarrow P_z^3$ will denote three pulses sequentially applied in line.

Shorthands succinctly describe patterns.

Moreover, tactile stimuli could have additional properties, such as waveform, frequency, and amplitude. These properties could be documented with indices. For example, $P_{sine}(l, 200)$ could denote a 200 ms pulse applied as sine wave, whereas P_{square} could denote a square wave. P_{200Hz} could specify the frequency of the stimulus, whereas $P_{200Hz, 20dB}$ could additionally specify the intensity.

Indices denote additional properties of tactile stimuli.

6.1.5 Tactile Suit and Hardware Setup

We have used tight-fitting cycling shorts and T-shirts with small pouches for actuators as a custom-tailored tactile suit for stimulating the body (see Fig. 6.4). Off-the-shelf Nokia 3270 cylindrical vibration motors served as

A tactile suit with cylindrical vibration motors



Figure 6.4: The first design of the tactile suit. Vibration motors were placed inside small pouches that were sewn on the fabric.

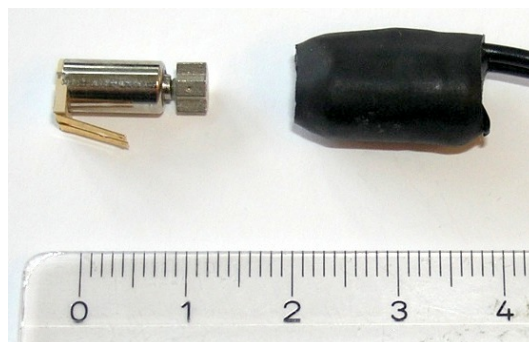


Figure 6.5: Nokia 3270 cylindrical motors were placed inside a plastic tube to shield the rotating mass. The tube was fixed with insulating tape and with heat shrinkable tubing. Strictly speaking, these motors create vibrotactile stimuli because they vibrate (see also section 5.2). Throughout this work, we will refer to these vibrotactile stimuli as tactile stimuli.

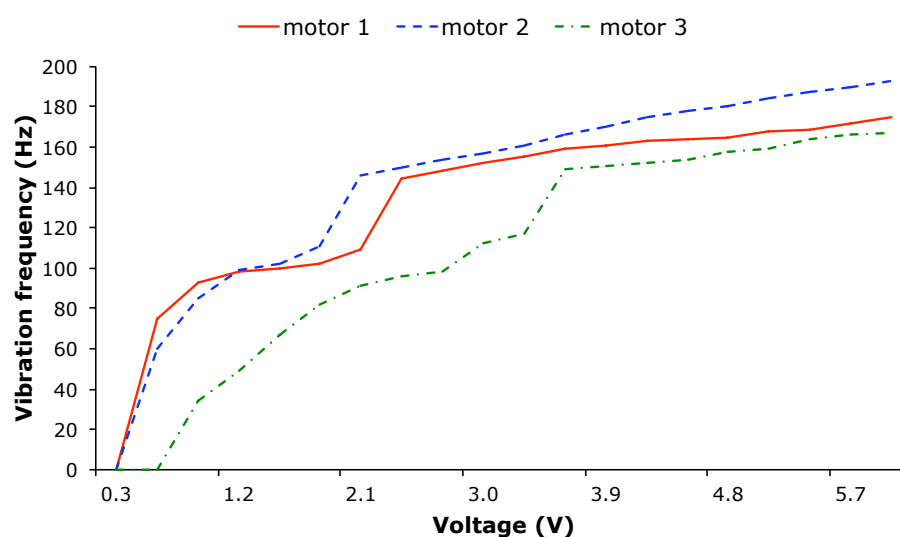


Figure 6.6: Nokia 3270 vibration motors were controlled by pulse width modulation to simulate different supply voltages [Barr, 2001]. The frequency range of motor three noticeably differed from those of the other motors for voltages below four V. The rotating mass of this motor might have slightly touched the plastic tube, or the layer of shrinking tube might have affected the vibration.

actuators (see Fig. 6.5). These motors were connected to the SensAct box (see Fig. 3.5) and were powered by four 1.5 V AA batteries (6 V).

The vibration frequency and intensity of these motors cannot be controlled independently; the higher the supply voltage is, the higher is the intensity and the frequency of the vibration. To estimate the characteristics of these motors, we have measured the vibration frequency of three motors. Each motor was fixated with superglue to an accelerometer type 4393 V for vibration measurement [Brüel & Kjær, 2009]. The motors were activated for 100 ms and were controlled by pulse width modulation at duty cycles between 0–100% [Barr, 2001], which simulated voltages up to the full supply voltage of six V. To prevent the motors and the cables from moving around, they were placed between two layers of foam, which was similar to placing them inside the pouches of our tactile suit.

The frequency and intensity of the vibration depend on the applied voltage.

Fig. 6.6 illustrates their vibration frequency. Overall, the examined motors vibrated at slightly different frequencies. The most notable characteristic was that voltages above four V yielded frequencies above 150 Hz. At full supply voltage, the average frequency was 178 Hz. Although these motors would not optimally stimulate the Pacinian corpuscles, which best respond to frequencies around 250 Hz (see Table 5.1), we decided to use these motors and to pulse them at full intensity. In a self-experiment in a static situation, we found that the evoked sensations were intense. Moreover, these Nokia 3270 vibration motors were comparable to vibration motors reported in related work on vibrotactile feedback. These motors vibrated at slightly

The motors vibrated at frequencies below 250 Hz.

lower frequencies without impairing the perception of the tactile stimuli: 80–100 Hz [Jones et al., 2006], 115 Hz [Jones et al., 2007], 142 Hz [Lindeman et al., 2004a], 160 Hz [Jansen et al., 2004, van Erp et al., 2005].

6.2 Intuitive Interpretation of Tactile Stimuli

Brainstorming ideas for representing body movements as tactile stimuli

Our first investigation in tactile motion instructions addressed the composition of tactile patterns that could be used for representing body movements in an intuitive way. Based on the stimuli depicted in Fig. 6.2, we have brainstormed various one-element, compound, and simultaneous patterns that could stimulate the body areas depicted in Fig. 6.3. We have identified 29 patterns that we gauged useful as starting points, including:

- Localized pulses at the torso

$$P^3(SRL), P^3(SLL), P^3(BMV_1), P^3(BMD_1)$$

- Directional lines based on sensory saltation at the torso

$$R_U(BRL), R_D(BRL), R_U(BMV), R_U(BMD)$$

- Rotation around the waist

$$P^3(BMV_3) \rightarrow P^3(BLL_3) \rightarrow P^3(BMD_3) \rightarrow P^3(BRL_3)$$

- Compound directional lines at opposing body sites

$$R_U(TLL) \rightarrow R_D(TRL), R_U(TRL) \rightarrow R_D(TLL)$$

- Simultaneous directional lines at the thighs

$$R_U(TRV) + R_U(TLV), R_D(TRD) + R_D(TLD)$$

A pilot study allowed us to identify problems with the tactile patterns.

A pilot study with two volunteers revealed that directional lines around the waist were not perceived as continuous movement when using the timing values illustrated in Fig. 6.2 (BD = 100 ms, IBI = 50 ms). For this reason, we considered shorter timing values for these patterns (BD = 50 ms, IBI = 30 ms) and included a pattern that rotated twice around the waist. Also, we found that testing all patterns was time-consuming. To limit the experimental time to one hour for each participant, we chose a between-subjects design and distributed the set of patterns between two user groups.

Exploratory study on the intuitive interpretation of tactile stimuli

Based on these patterns, we have conducted an exploratory study in order to observe how young adults intuitively responded to the tactile stimuli. An *open response paradigm* was used such that the participants could freely assign any meaning to the tactile sensations they experienced across the body. Moreover, they were encouraged to explain their thoughts and reactions. This qualitative data helped us to find tactile patterns that could naturally describe how to move the body.

Table 6.2: Average percentage of vague and concrete responses to all tactile patterns that comprised single localized pulses (P^3), single directional lines (R), simultaneous patterns (SP), and compound patterns (CP).

| Pattern category | P^3 | R | CP | SP |
|---------------------|-------|----|----|----|
| Vague responses | 35 | 21 | 30 | 37 |
| Concrete responses | 65 | 79 | 70 | 63 |
| Concrete movement 1 | 53 | 48 | 56 | 49 |
| Concrete movement 2 | 13 | 22 | 23 | 19 |
| Concrete movement 3 | 6 | 6 | 0 | 3 |
| Other movements | 28 | 24 | 21 | 29 |

6.2.1 Participants and Experimental Setup

Twenty volunteers aged 22–28 years ($M = 25.25$ years) were recruited from the local university (eight women). Nineteen volunteers regularly practiced sport. None of them had problems in perceiving tactile stimuli.

The participants were informed that they would perceive tactile stimuli at different locations across the body and that these cues were intended to represent body movements. Their task was to describe the perceived sensations and to explain with which body movements they associated these sensations. They were not aware of the characteristics and the composition of the stimuli. Neither did they know which body movements these chosen patterns could represent.

The participants stated which body movements the tactile stimuli could represent.

The experimenter used the SensAct Control application (see Fig. 3.9) to randomly trigger the tactile patterns. The participants stood upright, wore headphones, and listened to soft music, which blocked the auditory cues produced by the vibrating motors. This setup prevented the participants from locating the position of the motors on the body by sound. Upon perceiving a pattern, the participants took off the headphones and explained their thoughts. All sessions were videotaped in order to resolve unclear issues while interpreting the responses during data analysis after the study.

6.2.2 Results

The participants' intuitive reactions varied. Their responses included concrete movements, such as lift the arm, and vague movements, such as move the arm. For almost all tactile patterns, a few participants stated that they did not associate the evoked sensations with any specific body movements.

The answers varied across the participants.

For each tactile pattern, we counted how often the participants assigned the same, a similar, or a different meaning. This statistics revealed which body movements were most often named, which patterns were possible candidates for tactile instructions, and which patterns were too vague to evoke specific reactions. Table 6.2 summarizes the average percent agreement on body

Single directional lines were most often associated with a concrete body movement.

Table 6.3: The most frequent responses (in %) to the tactile patterns and the stimulated body areas.

| Location of localized pulses | Reactions as body movements |
|-------------------------------|--|
| Left or right shoulder | lift left arm (30%), move right arm (30%) |
| Both shoulders | pull back the shoulders (50%) |
| Upper chest | lean backward (30%) |
| Upper back | straighten up (50%), lean forward (30%) |
| Location of directional lines | Reactions as body movements |
| Chest (sternal) | lean/go backward (40%) |
| Back (spine) | straighten up (30%), lean forward (20%) |
| Lateral side of the torso | move arm away (50%), lean upper body sideways (40%) |
| Lateral side of the thighs | shift the weight to the other foot (40%), move the leg (20%) |
| Back or front of the thighs | bend the legs (60%), jump (20%) |
| Around the waist | turn left or right (60%) |

movements for all patterns of the same type. Overall, single directional lines (R) most often yielded a concrete answer that described a specific body movement. Several participants stated to prefer these patterns to localized pulses because they provided clear cues how to move the body. Although we found that every pattern could represent two or more body movements, clear trends towards one specific reaction emerged. Table 6.3 summarizes the most frequent answers and the body area that was stimulated. In the following paragraphs, we will summarize which tactile patterns the participants associated with which body movements.

Localized pulses prompted to move the stimulated body part.

The reactions to localized pulses were often vague and interpreted as request to move the corresponding body part somehow. Pulses at the left shoulder prompted to *lift the left arm* (30%), to *lean right*, to *move the shoulder forward*, or to *move the shoulder backward*. Pulses at the right shoulder prompted to *move the right arm* (30%), to *lean left*, to *lean right*, or to *move the shoulder forward*, but not to turn around. There was a broad agreement that pulses at the torso prompted to correct upper body posture, such as at the upper chest to *lean backward* (30%), at the upper back to *straighten up* (50%) or to *lean forward* (30%), and at both shoulders to *pull back the shoulders* (50%).

The responses to directional lines and to localized pulses at the back and the chest were similar.

The responses to directional lines R_U and R_D delivered to the back or to the chest yielded similar answers as single pulses. For example, $R_U(BMV)$ was interpreted as *lean/go backward* (40%) and once as *lean forward*. $R_U(BMD)$ yielded *straighten up* (30%), *lean forward* (20%), and once *lean backward*. Three participants followed the directional information rendered by $R_U(BMV)$ and $R_U(BMD)$; they responded with *pull the shoulders up*.

Lateral stimuli at the torso or the thighs often prompted to lean sideways.

Pulses and directional lines delivered laterally to the torso, such as $R_U(BRL)$ and $R_U(BLL)$, most often prompted to *move the arm away from the body* (50%) and to *lean the upper body sideways* (40%). $R_U(TRL)$ and

$R_U(TLL)$ delivered laterally to the thigh were interpreted as requests to *lift the leg* or to *shift the weight from one foot to the other foot* (40%), to *move the leg* (20%), and once to *lean the upper body sideways*.

Compound and simultaneous patterns that were delivered laterally to the thighs, such as $R_U(TRL) \rightarrow R_D(TLL)$ or $R_U(TRL) + R_D(TLL)$, produced a similar effect to one-element patterns, such as $R_D(TLL)$. Even so, four participants stated that compound patterns were contradictory; these patterns evoked countermovements. For example, when they perceived the pattern $R_U(TRL)$ laterally at the right thigh, they were tempted to *shift the weight towards the left foot*. They were, however, tempted to *shift the weight back towards the right foot* when the vibration $R_D(TLL)$ started at the left thigh. Simultaneous patterns laterally at both thighs demanded more attention to identify the direction that was displayed on the skin.

About 60% of the participants tended to move away from the particular side where vibration was delivered to the chest, to the back, and laterally to the torso or to the thighs. The other candidates tended to move towards on the side where they perceived the vibration.

R_D simultaneously delivered to both thighs was interpreted as *bend the legs* when the back or the front of the thighs was stimulated (60% vs. 40%). Although half of the participants could not interpret R_U at the back of the thighs, two participants stated to *bend the legs*, and two participants stated to *lean forward*. Similarly, the responses to R_U delivered to the front of the thighs varied and showed no clear trends to specific movements. Three candidates responded with *lean backward* and two with *jump upwards*.

Simultaneous patterns that activated all motors at the thighs were described as strong and as less pleasant (25%). About half of the participants could not interpret these patterns. For the other participants, R_D mostly felt like *bending the legs* (40%), R_U like *stretching* (20%) or *jumping* (20%). These patterns were rated to represent more powerful or faster movements than patterns that stimulated either the back or the front of the thighs.

The directional lines around the waist, which based on the standard timing values, resembled localized taps and were not perceived as continuous movement. Even so, they were associated with *turn left* or *turn right* a few times (30%). The patterns that based on the shorter timing values, which quickly delivered brief pulses and which were rendered twice around the torso, were more often interpreted as *turn left* or *turn right* (60%).

6.2.3 Discussion

This exploratory study on the intuitive interpretation of tactile stimuli revealed that young adults associated localized pulses and directional lines with specific body movements. These stimuli could serve for composing a general set of tactile patterns that could signal how to move the body.

Compound patterns laterally at the thighs sometimes evoked countermovements.

Moving towards vs. moving away from stimuli

Directional lines downward at the back of the thighs prompted to flex the legs.

Simultaneous patterns evoked strong and less pleasant sensations.

Quick directional lines around the waist signaled to turn sideways.

Tactile stimuli exist that can represent body movements in an intuitive way.

| | |
|---|---|
| The stimulated body areas were moved. | Overall, we found that a tactile stimulus applied to a specific body location lead to movements of the same body part. Sometimes, neighboring body parts were moved. This observation indicates that the message conveyed by a stimulus should be directly related to the stimulated body area. |
| A tactile pattern can represent different movements. | Although every participant mapped a tactile pattern only to one body movement, we found at least two different responses to this pattern across our user group. Consequently, if these patterns were used as instructions, the mapping between a pattern and its meaning would be obvious for some users, whereas other users would have to learn this mapping. Even so, learning the meaning of these patterns should not be difficult because none of the associated movements did address distant body locations. |
| A tactile stimulus can intuitively indicate a push or a pull of the body. | An interesting observation was that about half of the participants preferred to move away from pulses delivered laterally to the torso or laterally to the thighs, as if they were being pushed away. The other participants tended to move towards the stimulation, as if they were being pulled. These reactions also occurred for stimuli delivered to the back and to the chest. These opposing reactions suggest that tactile motion instructions could base on two encoding metaphors that represent either a <i>push</i> or a <i>pull</i> of the body. Moreover, these metaphors would allow us to design expressive sensations that feel realistic (see section 6.1). To illustrate the difference between these two approaches, assume that you were instructed to <i>lean your body to the left</i> . The <i>pull</i> technique would display the impulse on the left side of the body to pull you to the left. In contrast, the <i>push</i> technique would display the impulse on the right side of the body to push you to the left. |
| Directional lines can provide strong cues how to move the body, and they could represent the bending radius of the torso. | Moreover, our findings indicate that directional lines delivered across larger body areas could intuitively encode the direction in which to perform a movement. Many participants preferred these cues because the evoked sensations signaled the direction in which to move, such as downwards for flexing the legs, or upwards for jumping or for pulling up the shoulders. When applied laterally to the torso, these patterns resembled the natural movements of the body when bending sideways. The higher the pulses traveled upwards, the higher these pulses corresponded to the bending radius of the torso (see section 5.4.2 and [Rupert, 2000], who mentioned that an increased tilt of the aircraft to the side could activate actuators located higher on the corresponding side of the pilot's torso). |
| Stimulating the lateral sides of the body in succession could evoke countermovements. | Although a stimulus that is applied laterally to the body could signal to lean sideways or to shift the weight to one foot, applying a subsequent stimulus at the opposing side of the body could result in a countermovement. This reaction to a compound pattern that stimulates both sides of the body is plausible if we assume that a user prefers to move either towards or away from the side where the stimulation occurs. For this reason, it seems to be beneficial if only one side of the body is stimulated. |
| Limitations of the study | The findings of this study can be used for designing tactile motion instructions. Even so, the experimental setup influenced and skewed the results. For example, we have focused on young adults. Consequently, the results |

are less representative for other age cohorts. To limit the time for conducting the experiment with each participant, we have split the chosen patterns in two sets, and we have chosen a between-subjects design. Also, some of the observed reactions were vague and difficult to classify.

The context in which the tactile patterns were tested further influenced how the participants responded. Our participants stood upright. This could explain why R_U delivered to the thighs was inexpressive and did not clearly prompt to stretch the legs. In contrast, R_U delivered to the torso resulted in *pull the shoulder up*, and R_D delivered to the thighs resulted in *flex the knees*; these movements could be performed while standing upright. Moreover, our participants knew that vibration motors generated the tactile sensations. This could explain why they did not turn around upon perceiving the pulses at the shoulders or at the back; it was not a person who touched them from behind. Had we informed the participants that these stimuli could represent instructions for navigating towards a target, we surmise that they might have turned around.

The situation influenced how the tactile patterns were interpreted.

Moreover, we have explored only a small set of tactile stimuli and did not vary their intensity. All pulses were delivered at full intensity (on or off), which feels jerky on the skin. Also, vibration over bones, such as at the ribs or the shoulder blades, feels harder than vibration over soft or muscular areas, such as at the belly or the thighs. Initially, we have observed sudden and jerky movements because our participants were not familiar with the evoked sensations. Moreover, the lateral sides of the torso seemed to be more sensitive because pulses at these locations were occasionally rated as ticklish but also as stronger than at other body areas. We surmise that smoother sensations, which pulses of increasing and decreasing intensities could evoke, might be associated with fluent body movements. In contrast, activating several motors simultaneously could create strong sensations that might represent wider or stronger movements: jumping instead of stretching the legs; turning around 360° instead of turning the upper body around the spine. In fact, some participants pointed out that such patterns might represent more powerful and wider body movements.

The characteristics of the tactile stimuli influenced the responses.

6.2.4 First Design Recommendations

Based on the participants intuitive responses to tactile stimuli, we can distill first recommendations for composing tactile patterns that could represent specific body movements:

- Body location should encode which part of the body to move.
- Directional lines could encode the direction in which to perform a movement, such as to flex the legs or to turn to the left.
- The mapping between a stimulus and its meaning could represent a push or a pull of the body towards the direction to move.

Table 6.4: Ten body movements that could serve as general instructions. Every movement has a corresponding countermovement.

| Body movement | Acronym | Category |
|--|---------|----------|
| Stretch the legs | SL | C1 |
| Flex the legs | FL | |
| Shift the weight from the right to the left foot | WL | C2 |
| Shift the weight from the left to the right foot | WR | |
| Lean the upper body to the left | LL | C3 |
| Lean the upper body to the right | LR | |
| Lean the upper body forward | LF | C4 |
| Lean the upper body backward (straighten up) | LB | |
| Turn the upper body to the left | TL | C5 |
| Turn the upper body to the right | TR | |

- A sequence of tactile stimuli that starts laterally at one side of the body and that concludes laterally at the opposing side could evoke countermovements. These patterns seem to be less appropriate for signaling lean left (right) and shift the weight to the left (right) foot.

Ten body movements as instructions

Considering the participants' most frequent responses to the investigated tactile patterns, we have chosen ten body movements that could serve as a general set of instructions in various physical activities (see Table 6.4). To represent these instructions as tactile patterns, we have chosen single directional lines, which our participants tended to prefer to localized pulses. Also, our findings indicated that simultaneous and compound patterns did not provide additional benefits over single directional lines.

The first set of tactile motion instruction patterns

Fig. 6.7 illustrates the locations where these directional lines could stimulate the body and describes the possible meaning of these patterns. The formal notation for these patterns is (see Fig. 6.3 for the acronyms on body locations and Table 6.4 for the acronyms on body movements):

Stretch the legs, flex the legs:

- $SL = R_U(TRV) + R_U(TLV)$ at the front of the thighs
- $FL = R_D(TRD) + R_D(TLD)$ at the back of the thighs

Shift the weight to the left / right foot:

- $WL = R_U(TRL)$ laterally at the right thigh
- $WR = R_U(TLL)$ laterally at the left thigh

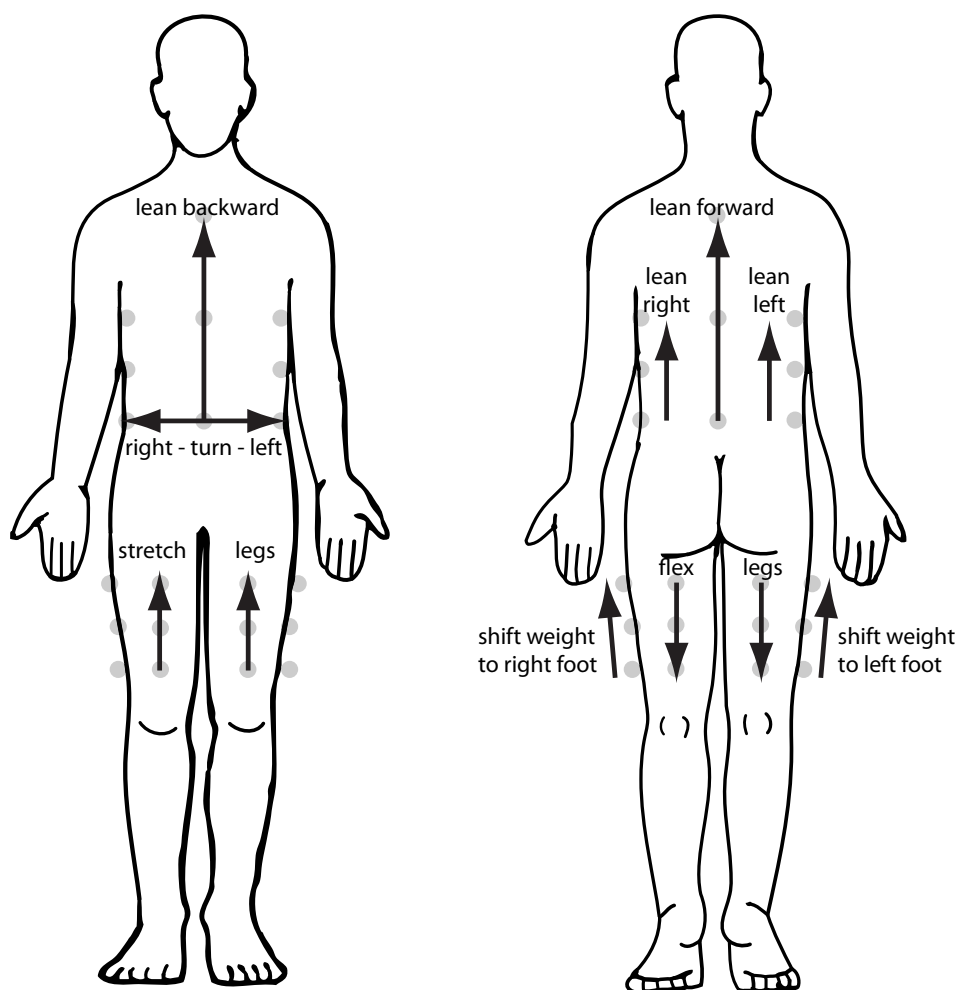


Figure 6.7: The first set of tactile motion instruction patterns, based on directional lines. The arrows indicate the direction of the evoked sensations. The lateral stimuli in upward direction at the torso and the thighs, and the stimuli applied to the front and back of the torso could be described to represent the increased bending radius of the body when leaning sideways, forward, or backward. The mapping between these patterns and their meaning bases on the push metaphor, which would prompt to move the body away from the side where the vibration is perceived. The stimuli at the front and back of the thighs resemble the pull metaphor; they could be described to pull flexed legs upwards or to pull stretched legs downwards.

Lean upper body to the left / right:

- $LL = R_U(BRL)$ laterally at the right side of the torso
- $LR = R_U(BLL)$ laterally at the left side of the torso

Lean upper body forward / backward:

- $LF = R_U(BMD)$ at the back

- $LB = R_U(BMV)$ at the chest

Turn upper body to the left / right:

- $TL = 2 \cdot (P_3^3(BMV) \rightarrow P_3^3(BLL) \rightarrow P_3^3(BMD) \rightarrow P_3^3(BRL))$
- $TR = 2 \cdot (P_3^3(BMV) \rightarrow P_3^3(BRL) \rightarrow P_3^3(BMD) \rightarrow P_3^3(BLL))$

The duration of these patterns is 1300 ms (BD = 100 ms, IBI = 50 ms, see Fig. 6.2). TL and TR last for 1890 ms (BD = 50 ms, IBI = 30 ms).

These design recommendations and the tactile patterns are not yet definite. They were derived from a stationary situation and do not consider how well they can be perceived and recognized in active situations.

6.3 Tactile Motion Instructions in Stationary and in Active Situations

Perception of tactile stimuli under physical activities

We have noted that cognitive workload can degrade the ability to identify the location of tactile pulses applied to the torso and the direction of sensory saltation applied to the back (see section 6.1.2). In the studies that investigated these stimuli, however, only a small area of the skin was stimulated. Moreover, demanding physical activities that could occur, for example, in sports training were not considered. To address these limitations of related work, we have investigated if young adults could perceive and identify our first set of tactile patterns while practicing sports that were physically and cognitively demanding. The findings of our studies provided additional guidelines for refining the chosen tactile motion instruction patterns.

Snowboarding and horseback riding as example activities

We have focused on snowboarding and on horseback riding because both activities do not allow coaches to always provide instructions in time or to physically move by hand the athlete's body into correct position. Moreover, in both sports, athletes experience cognitive workload, natural forces, and vibration that could influence how they perceive artificial tactile stimuli. Snowboarders wear thick, tight-fitting clothes and boots that create natural tactile sensations. The harsh environment leads to cold limbs, pain, and muscle strains. Snowboarders also have to quickly adjust their posture for maintaining balance, and they have to choose a riding path that does not endanger other winter sport practitioners. Although horseback riding is physically less demanding than snowboarding, this sport involves different body movements and puts a different cognitive workload on equestrians.

6.3.1 Perception under Increasingly Realistic Conditions

We used the Wii balance board to simulate an active situation.

Before conducting field experiments, we have evaluated our first set of tac-



Figure 6.8: The cognitive and physical workload condition of the experiment required the participants to respond to tactile motion instructions on the Wii balance board. The actuator boxes were placed inside a backpack.

tile patterns under laboratory conditions. The *Nintendo Wii Fit* balance board [Nintendo, 2010] and the game *Slalom Snowboard* served to simulate an active situation similar to real snowboarding (see Fig. 6.8). Standing on a short and narrow static board that represented the snowboard, our participants had to redistribute their weight between the toes and the heels for passing between flags shown on a 40-inch display. To maintain balance, they had to slightly flex the legs and to move the upper body and the arms. Shifting the weight to the front foot accelerated the snowboard, whereas shifting the weight to the back foot decreased its speed. In contrast to real snowboarding, playing this game was physically less exhausting and did not require the participants to wear thigh and thick clothes.

A pilot study with two volunteers revealed that almost all movements were spasmodic and difficult to classify. Moreover, the experimenter could not accurately differentiate if the participants moved their bodies as response to tactile instructions or if these movements were required in the current gameplay situation. Therefore, we asked our participants to first utter which instruction they perceived before executing this instruction. These additional verbal responses, however, increased the cognitive workload on them while playing the game.

The participants had to utter the perceived instructions and to perform the movements.

Participants and Experimental Setup

Twenty volunteers aged 19–30 years ($M = 24.83$ years) were recruited from the local university (four women). All volunteers regularly practiced sport,

such as jogging or fitness exercises. Three participants snowboarded. Five participants had already played with the balance board. Nine volunteers had participated in our first study on the intuitive interpretation of tactile stimuli (see section 6.2).

We have compared the perception of tactile motion instructions in stationary and active situations.

If tactile instructions were applied in a realistic setting during sports training, such as during a snowboarding course, snowboard students would first learn the meaning of these instructions before they would respond to them during exercises. Therefore, our goal was to investigate how physical and cognitive workload influenced the ability to perceive and discriminate between tactile instructions immediately after learning the meaning of the tactile patterns. We chose a within-subjects design with two conditions:

1. Stationary situation
2. Active situation (Wii balance board)

The participants learned the tactile instructions and practiced the game.

We chose the push metaphor as mapping between the patterns and their meaning in order to keep the instructions consistent for all participants (see Fig. 6.7). The participants learned the meaning of the ten patterns for up to ten minutes by pressing buttons on the GUI of the SensAct Control application (see Fig. 3.9). Each button represented an instruction, such as *Flex the legs*, and triggered the corresponding tactile stimuli. This training phase concluded with two to three practice runs on the balance board, which allowed all participants to become familiar with the game.

Upper and lower body instructions were tested separately.

Testing all patterns necessitated five SensAct boxes (see Fig. 3.5), which were uncomfortable to wear in a backpack and which could hinder the participants in moving their bodies. To increase the participants' freedom of movement while playing the game, we decided to reduce the weight of the backpack. We used three boxes and applied the instruction sets for the upper and lower body separately. The order in which these instruction sets were applied was counterbalanced across the participants.

The stationary situation served as baseline for optimal perception.

In the first condition, we measured how accurately randomly delivered instructions were recognized in a stationary situation while standing still. These measurements represented the baseline for the optimal perception of tactile instructions. The participants stood upright and listened to soft music played back through headphones, which blocked the auditory cues from the vibrating motors. Their task was to state which instructions they had perceived and to perform the corresponding body movements. All instructions were applied for two times.

The participants uttered the recognized instructions while playing the game.

For the second condition, the candidates were asked to first say out aloud the perceived instructions and then to perform the corresponding movements while playing the game. The experimenter randomly triggered all instructions, using a random delay of 10–15 seconds after the participants uttered their responses. The participants replayed the game until all instructions were applied for two times. After the experiment, we informed the participants which instructions they had misinterpreted.

Table 6.5: Average accuracy in identifying instructions in a stationary situation and in an active situation on the Wii balance board (in %, with standard deviation).

| | Situation | Group A | Group B | Both groups |
|-------|------------|---------------------|---------------------|--------------|
| Day 1 | stationary | 96.11 (6.97) | 98.13 (2.59) | 97.06 (5.32) |
| | active | 91.67 (8.30) | 97.50 (5.35) | 94.41 (7.48) |
| | both | 93.89 (7.78) | 97.81 (4.07) | 95.74 (6.53) |
| Day 2 | stationary | 97.78 (5.06) | 94.38 (9.04) | 96.18 (7.19) |
| | active | 92.78 (6.67) | 95.63 (5.63) | 94.12 (6.18) |
| | both | 95.28 (6.29) | 95.00 (7.30) | 95.15 (6.68) |

The experiment was repeated on the following day in order to assess how well the participants recalled the meaning of the tactile patterns in both situations. Therefore, we asked the participants if they could return for an additional experiment. To avoid practicing the meaning of the patterns at home, we did not tell them the purpose of the follow-up experiment.

The experiment was repeated on the following day.

Results

Three volunteers were not able to participate on the second day and were excluded from data analysis. The other participants were split into two groups to consider their previous experience with artificial tactile stimuli in relation to our technology. Group A comprised the nine volunteers who were new to these stimuli. Three participants had tried the balance board before. One participant snowboarded. Group B comprised the eight volunteers who had participated in the first study on the intuitive interpretation of tactile stimuli. Although they did not know the final composition of the patterns, they might have benefitted from their previous experience with these stimuli. Two participants had tried the balance board before. Two participants snowboarded.

The participants were split into two groups to consider their previous experience with artificial tactile stimuli.

None of the volunteers used the allotted time of ten minutes for learning the meaning of the instructions. On average, they finished after 3–4 minutes.

Short learning time

The participants did not miss instructions. They perceived and responded to all instructions in the stationary and active situation. Even so, some participants misinterpreted a few instructions with the corresponding counter-instructions. One participant explained that he had difficulties in articulating the meaning of the patterns. Although he recognized the instructions, he tended to mix up the directions when responding verbally. For example, he noticed to answer left instead of right and right instead of left. Moreover, some volunteers stated that they preferred to express the meaning of the patterns with gestures of the hands and arms in order to avoid speaking.

All instructions were perceived, but some were misinterpreted when responding verbally.

Table 6.5 summarizes the average percentage of recognized instructions for each group. A mixed between-within ANOVA revealed no significant main effect of the group, $F(1, 15) = 1.20, p = .29, r = .27$. This indicates that

Previous experience with tactile stimuli did not significantly improve the performance.

the ability to recognize instructions was in general the same for participants who did not have previous experience with tactile stimuli in relation to our technology (group A) and for participants who had participated in our first experiment on the intuitive interpretation of tactile stimuli (group B).

Instructions were recognized with similar accuracy on both days and in both situations.

There was no significant main effect of the day, $F(1, 15) = .12, p = .73, r = .09$, indicating that instructions were recognized with similar accuracy on both days. There was no significant main effect of the situation, $F(1, 15) = 2.75, p = .12, r = .39$, indicating that the ability to respond to instructions was in general the same in the active and stationary situation.

No interaction effect for day \times group, situation \times group, and day \times situation.

There was no significant interaction effect between the day and the group, $F(1, 15) = 1.07, p = .32, r = .26$. This indicates that both groups recognized instructions with similar accuracy on both days. There was no significant interaction effect between the situation and the group, $F(1, 15) = 3.59, p = .08, r = .44$. Although this indicates that both groups recognized instructions with similar accuracy in both situations, group A recognized fewer instructions than group B in the active situation, but this difference in performance was not significant. There was no significant interaction effect between the day and the situation, $F(1, 15) = .08, p = .78, r = .07$. This indicates that on both days the instructions were recognized with similar accuracy in both situations.

Overall, neither the situation nor the day nor the experience with tactile instructions significantly influenced the participants' performance.

The day \times situation \times group interaction was not significant, $F(1, 15) = .27, p = .61, r = .13$. This suggests that the ability to recognize tactile instructions did not depend on the situation, on the day, or on the participants' previous experience with tactile stimuli. Although the average number of recognized instructions was in general lower for group A than for group B and lower in the active situation than in the stationary situation, this difference in performance between the groups and between the situations was not significant. In addition, the participants remembered the meaning of the ten instructions on the following day without practice in-between. Even so, the participants were told after the experiment on the first day which instructions they had misinterpreted, which could have affected their responses on the second day.

Upper body rotation and knee flexion/extension were most often misinterpreted.

Fig. 6.9 shows which instructions group A recognized. Amongst all instructions, *Turn left* and *Turn right* were most often misinterpreted in both situations and on both days. *Stretch (flex) the legs* were most often misinterpreted on the first day. Fig. 6.10 shows which instructions group B recognized. On the first day, only the instructions *Turn left*, *Turn right*, and *Lean right* were misinterpreted a few times. This group's performance slightly degraded on the second day when two participants additionally misinterpreted *Stretch (flex) the legs* in both situations. The ability to recognize the other instructions was similar between the groups.

The profiles of the recognized instructions did not significantly differ between the groups on day 1.

On average, in the stationary situation on day 1, group A recognized the instructions with similar accuracy ($M = 96.11\%$, $SE = 1.67\%$) as group B ($M = 98.13\%$, $SE = .95\%$); the difference between the profiles of the recognized instructions was not significant $t(14.33) = -1.05, p = .31, r = .24$ (in-

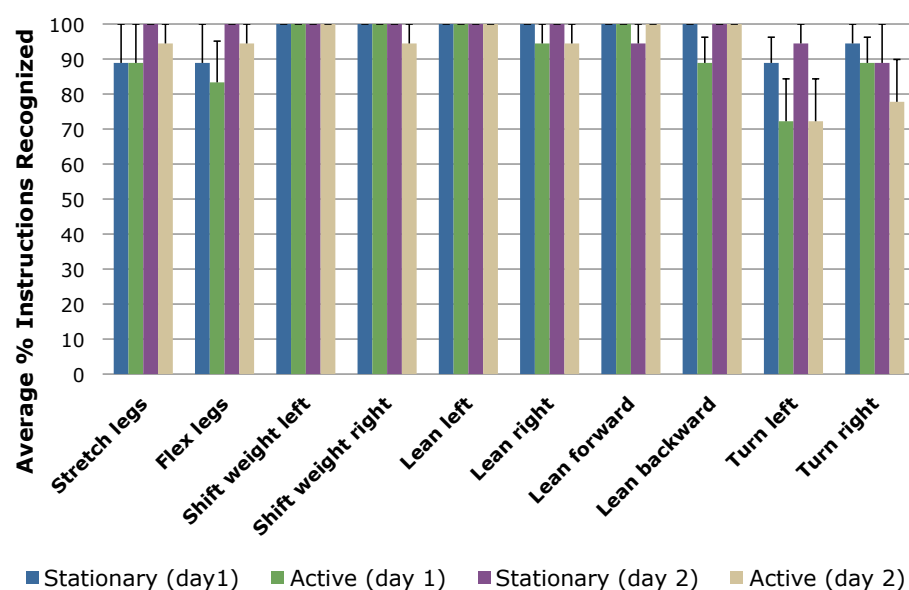


Figure 6.9: Average percentage of recognized instructions for group A (with standard error).

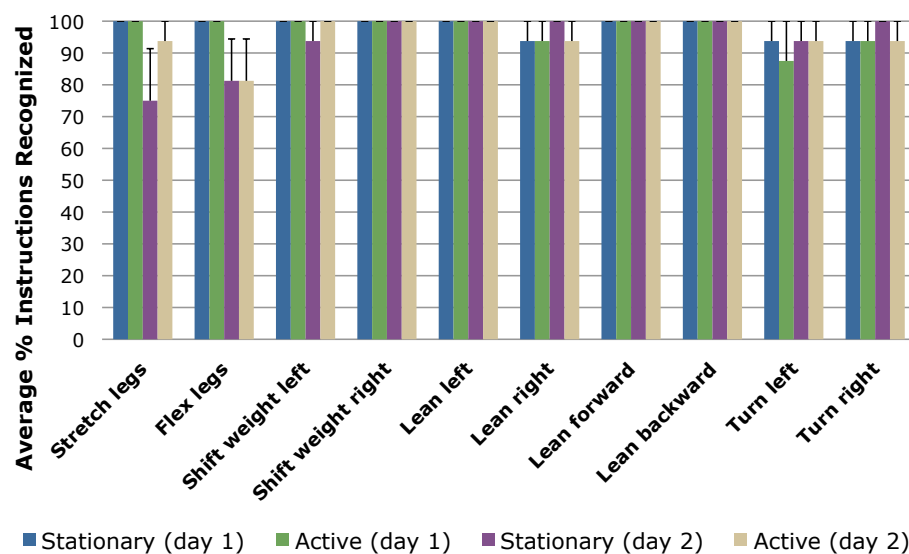


Figure 6.10: Average percentage of recognized instructions for group B (with standard error).

dependent t-test, two-tailed, equal variances not assumed). In the active situation on day 1, group A recognized fewer instructions ($M = 91.67\%$, $SE = 2.90\%$) than group B ($M = 97.5\%$, $SE = 1.38\%$), but the difference between the profiles was not significant $t(18) = -1.82$, $p = .09$, $r = .39$ (independent t-test, two-tailed, equal variances assumed).

On average, in the stationary situation on day 2, group A recognized more instructions ($M = 97.78\%$, $SE = 1.23\%$) than group B ($M =$

The profiles of the recognized instructions did not significantly differ between the groups on day 2.

Table 6.6: Number of participants who misinterpreted at least once an instruction (see Table 6.4 for categories). The row “distinct users” denotes the number of different participants across both situations.

| | | Situation | C1 | C2 | C3 | C4 | C5 |
|---------|-------|----------------|----|----|----|----|----|
| Group A | day 1 | stationary | 1 | | | | 2 |
| | | active | 2 | | 1 | 2 | 5 |
| | | distinct users | 2 | | | | 6 |
| | day 2 | stationary | | | | 1 | 1 |
| | | active | 1 | 1 | 1 | | 6 |
| | | distinct users | | | | | 6 |
| Group B | day 1 | stationary | | | 1 | | 2 |
| | | active | | | 1 | | 1 |
| | | distinct users | | | 2 | | 2 |
| | day 2 | stationary | 2 | 1 | | | 1 |
| | | active | 2 | | 1 | | 2 |
| | | distinct users | 3 | | | | 2 |

94.38%, $SE = 2.86\%$); the difference between the profiles was not significant $t(18) = 1.09, p = .29, r = .25$ (independent t-test, two-tailed, equal variances assumed). In the active situation on day 2, group A recognized fewer instructions ($M = 92.78\%, SE = 3.10\%$) than group B ($M = 95.63\%, SE = 1.88\%$); the difference between the profiles was not significant $t(18) = -.79, p = .44, r = .18$ (independent t-test, two-tailed, equal variances assumed).

Group A had difficulty in recognizing the direction of rotation around the waist in the active situation.

Table 6.6 summarizes the number of participants who misinterpreted instructions. Five to six members of group A had difficulties in discriminating the instructions of category C5 (*Turn left or right*) in the active situation on both days, whereas only two members of group B misinterpreted these instructions. Two to three members of either group misinterpreted the instructions of category C1 (*Stretch or flex the legs*). One to two members of each group misinterpreted other instructions. One member of group A and two members of group B—one snowboarder—recognized all instructions.

Rotational patterns required paying attention to the stimuli.

All participants responded to all instructions. Even so, some participants mentioned that although they had perceived vibration around the waist, they could not identify in which direction to turn without paying attention to these stimuli. Those volunteers who balanced on the board for the first time apparently had more difficulties than those who had already played with the board. Also, the anatomy of the body influenced the perception of the stimuli while playing the game. Some participants pointed out that they had noticed vibration at the belly and the upper back but seldom at the lower back and the chest. This indicated that our tactile suit was less appropriate for displaying directional lines along the spine and sternum.

Discussion

This study investigated if young adults could perceive and identify tactile instructions in a stationary situation and in an active situation during a balance task. These instructions were based on directional lines that were rendered across the entire body. Overall, all participants quickly learned and recalled the meaning of the tactile patterns over a period of two days. They recognized most of the instructions with high accuracy in the stationary and in the active situation, independent of their pre-experience with artificial tactile stimuli. Moreover, they did not miss instructions in the active situation.

The balance task did not degrade the perception of tactile stimuli.

These findings indicate that the physical effort and the cognitive workload experienced during the balance task did not degrade the ability to perceive the tactile stimuli. Even so, several participants misinterpreted some instructions, in the active situation in particular. This indicates that the balance task degraded their ability to identify and to name the meaning of the patterns compared to the stationary situation. The instructions for turning left (right) and for stretching (flexing) the legs were most often misinterpreted, but the reasons why these instructions were misinterpreted are different.

Some tactile patterns were misinterpreted.

The tactile patterns that represented *Turn left* and *Turn right* were delivered to the same body location and only differed in their direction around the waist. In general, patterns that share actuators are difficult to discriminate [Geldard and Sherrick, 1965, Cholewiak and Collins, 1995]. In our case, six members of group A misinterpreted these patterns. At first sight, it seems that members of group B benefitted from their previous experience with artificial tactile stimuli because only two of them misinterpreted these patterns. The characteristics of these patterns, however, suggest that group B had less difficulty in paying attention to the direction of these patterns while balancing on the board than group A. Therefore, these patterns have to be modified to ensure that end-users can discriminate between them regardless of the workload that they might experience in active situations.

The patterns for turn left and turn right have to be modified.

In contrast, the patterns that represented *Stretch (flex) the legs* stimulated opposing body sites and did not share actuators. Only a few members of either group misinterpreted these instructions, which indicates that these patterns are discriminable. Even so, a few participants misinterpreted these instructions in the stationary situation when they did not experience cognitive workload that could have degraded their ability to pay attention to these distinct stimuli. This indicates that these participants might have benefitted from more training for learning the meaning of these patterns.

The instructions are easy to learn, but the practice session could be longer.

Besides these issues, our participants uttered the meaning of the instructions, which could have lead to misinterpretations while playing the game. Many people have trouble telling left from right (*left-right confusion*) [Hannay et al., 1990], in particular under time pressure. In fact, one participant pointed out that he had recognized the instructions but had mixed up the

Speaking distracted during the game.

directions while speaking. Also, some participants might have benefitted from executing the instructions before speaking, which would have put a different cognitive workload on them. With hindsight, we can attribute delayed responses to the fact that speaking required attention.

Random instructions might have interfered with the required movements for playing the game.

Moreover, we assume that our experimental setup could have influenced the participants' responses. Since all instructions were randomly delivered during the game, they did not occur at times when corrections were required. For example, the message to turn the body to the right could have interfered with turns to the left while passing the flags on the screen, which could have lead to incorrect responses.

The push metaphor did not cause problems.

The instructions for leaning sideways, forwards, and backwards were based on the push metaphor to indicate in which direction to move. Since only a few of these instructions were misinterpreted, we can conclude that this encoding metaphor did not cause problems. Even so, the effects of the encoding metaphor should be further investigated because our previous results indicated that some people intuitively prefer to move towards the points of stimulation instead of away (see section 6.2).

Our findings indicate that tactile motion instructions can be perceived and recognized with high accuracy in an active situation.

In conclusion, our findings indicate that the active situation did not degrade the ability to perceive the chosen tactile stimuli on the body compared to the static situation. The findings also indicate that those volunteers who had participated in our first experiment on the intuitive interpretation of tactile stimuli did not benefit from their previous experience with these stimuli. Even those volunteers who were new to the tactile patterns quickly learned and recalled the instructions. Moreover, the profiles of the recognized instructions did not significantly differ between the groups, which indicates that both groups recognized the ten instructions with similar accuracy in the static and active situation. Even so, the ability to recognize the direction of rotation around the waist degraded in the active situation. Also, several participants misinterpreted some instructions when they uttered the meaning of the patterns while playing the game.

6.3.2 Perception under Real-World Conditions: Snowboarding

We tested tactile instructions on the slope.

The previous study was conducted in the laboratory and considered a balance task for controlling a virtual snowboard. We decided to repeat the experiment under realistic conditions with users on the slope, as this environment initially motivated us to design tactile motion instructions. This study was conducted by Jacobs [2008] under the guidance of the author.

Overall, we expected that the ability to perceive and to interpret the designed tactile patterns would degrade compared to the laboratory condition. Snowboarders have to continuously pay attention to maintaining balance. They face exciting situations, they wear thick and tight clothes, and they experience muscle strains and pain. These conditions could degrade the



Figure 6.11: A backpack stored the SensAct boxes during the ride.

perception of tactile pulses, as indicated in related work (see section 6.1.2).

To estimate if the composed tactile patterns were appropriate as instructions during physical activities, we have introduced spoken instructions played back over earplugs. Spoken instructions are commonly used for teaching motor skills, and they might be preferred by athletes. The accuracy in recognizing these messages served as baseline for optimally perceiving instructions during descents.

We compared tactile instructions to spoken instructions.

Participants

Ten snowboarders aged 23–28 years ($M = 25.4$ years) were recruited over e-mail with help from the local university's sports center (four women). On a scale ranging from level one (beginner) to level five (expert), two volunteers rated their skills as level two (advanced beginner), six as level three (advanced), and two as level four (proficient). They snowboarded between one and three weeks per year during holidays. One advanced snowboarder had previously participated in the initial study on the intuitive interpretation of tactile stimuli (see section 6.2).

Ten snowboarders with different riding skills participated.

Hardware Setup

The participants carried three SensAct boxes (see Fig. 3.5) in a backpack (see Fig. 6.11) and two time-synchronized Nokia N70 mobile phones in their pockets. One of the Nokia N70 ran a Python script that controlled the boxes and that triggered the tactile instructions. Alternatively, this host

Table 6.7: Eight instructions were rephrased and adapted to metaphors used in snowboard training (see Table 6.4 for the original wordings). The column “Duration” denotes the length of the German wordings in seconds.

| English wording | German wording | Duration | Acronym |
|---------------------------|-------------------|----------|---------|
| Fries | Pommes | 0.8 | SL |
| Burger | Burger | 0.8 | FL |
| Pressure towards the nose | Die Nose belasten | 1.7 | WL |
| Pressure towards the tail | Das Tail belasten | 1.7 | WR |
| Lean towards the nose | Zur Nose lehnen | 1.7 | LL |
| Lean towards the tail | Zum Tail lehnen | 1.7 | LR |
| Lean upper body forward | Nach vorne lehnen | 1.5 | LF |
| Straighten up | Aufrichten | 1.1 | LB |
| Hello valley | Hallo Tal | 1.1 | TL |
| Hello mountain | Hallo Berg | 1.1 | TR |

device played back spoken instructions. All instructions were time-stamped and logged for off-line data analysis. The other Nokia N70 recorded the participants’ utterances using a microphone that was attached to the collar of the jacket. This setup was necessary because it was too difficult for the experimenter to manually trigger the instructions while descending the slope and to observe if the participants performed the required movements.

Experimental Setup

The study took place in the indoor ski resort SnowWorld Landgraaf, The Netherlands. The slope was 520 m (1700 ft) long. This slope was open to other winter sport practitioners during the experiment. The temperature was -5°C .

The wording of the instructions was adapted to resemble real exercises.

The meaning of the instructions was rephrased to represent snowboarding exercises that coaches would issue during courses (see Table 6.7). Moreover, these wordings guided the snowboarder’s attention to the external effects of the movements instead of to the body, which is considered beneficial for training [Wulf, 2007] (section 8.1 discusses why the wording of feedback is an important factor in motor skill learning).

The patterns for turning left (right) were modified.

The tactile patterns that represented upper body rotation (TL, TR) were modified to provide additional cues in which direction to turn. These new patterns based on the push metaphor: pulses that started and ended at the right side of the abdomen signaled to turn left; pulses that started and ended at the left side of the abdomen signaled to turn right. The duration of these patterns (2130 ms) reached the maximum length of two seconds that was recommended for tactile messages [Geldard, 1957].

Localized pulses at the shoulder blades signaled to lean forward.

A pilot study with two male volunteers revealed that the underclothes, which winter sport practitioners typically wear, degraded the perception of

the directional line rendered along the spine. This line signaled to *Lean forward* (LF). To ensure that this instruction was perceived, we replaced this line with three localized pulses at the shoulder blades (400 ms).

The formal notation of these three modified patterns is (see Fig. 6.3 for the acronyms on body location):

- $LF = P^3(SLD) + P^3(SRD)$
- $TL = 2 \cdot (P_3^3(BRL) \rightarrow P_3^3(BMV) \rightarrow P_3^3(BLL) \rightarrow P_3^3(BMD)) \rightarrow P_3^3(BRL)$
- $TR = 2 \cdot (P_3^3(BLL) \rightarrow P_3^3(BMV) \rightarrow P_3^3(BRL) \rightarrow P_3^3(BMD)) \rightarrow P_3^3(BLL)$

We chose a within-subjects design with two conditions:

- Tactile instructions
- Verbal instructions played back over earplugs

The experiment comprised eight descents, which were scheduled for the morning and after the lunch break. Four descents addressed tactile instructions. The other four descents addressed spoken instructions. For each modality, two descents addressed the instructions for the upper body, whereas the other two descents addressed the instructions for the lower body. The order in which the modality and the two instruction sets were applied was counterbalanced across the participants.

Four descents addressed tactile instructions; four descents addressed verbal instructions.

The participants learned the meaning of the tactile patterns before the corresponding descents. The experimenter triggered each instruction twice and demonstrated the body movements. The instructions were repeated on request until the participants were sure to have memorized their meaning.

The host device was programmed to randomly trigger the instructions with a random delay of 5–10 seconds until the program was manually stopped. The participants' task was to say out aloud which instruction they perceived and to perform the corresponding movement unless this movement hindered their riding technique. After the experiment, they answered a questionnaire asking their view on tactile and spoken instructions while snowboarding (see Appendix B).

The participants uttered the instructions and performed the movements.

Results

The audio recordings revealed wind-noise and the noise of the snowboard shoving snow away. This allowed us to differentiate when the participants descended and when they stopped at the end of the slope. Overall, each

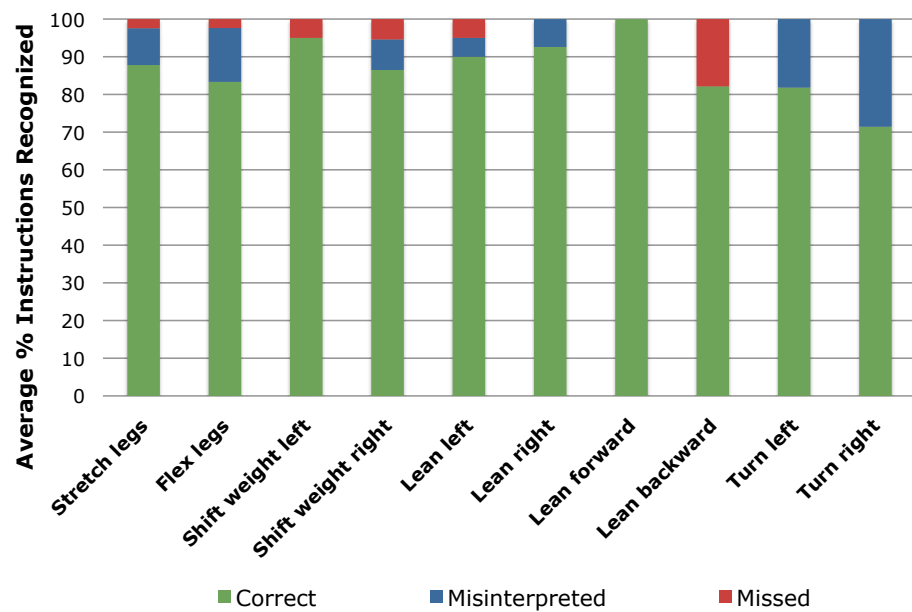


Figure 6.12: Average percentage of recognized tactile instructions while snowboarding.

participant experienced every instruction at least once in both conditions. Nevertheless, since the participants descended the slope at different speed, the number that an instruction was applied slightly differed among the participants. For this reason, we have considered all instructions that were applied after starting to descend and before coming to a halt.

The perception of verbal instructions was near-perfect.

Spoken instructions were perceived with near-perfect accuracy. On average, the participants recognized 97.15% ($SD = 4.24\%$), missed 1.60% ($SD = 2.61\%$), and misinterpreted 1.25% ($SD = 2.64\%$) of these messages.

A few tactile instructions were missed or misinterpreted.

Fig. 6.12 shows the profile of tactile instructions. On average, 87.06% ($SD = 8.03\%$) of instructions were recognized, 9.13% ($SD = 9.18\%$) were misinterpreted, and 3.81% ($SD = 5.42\%$) were missed. One woman recognized all patterns. The modified pattern for *Lean forward* (LF) was recognized in all trials. Four snowboarders (three women) did not respond a few times to the instruction *Lean backward* (LB), which was delivered along the sternum.

Upper body rotation and knee flexion were most often misinterpreted.

The participants most often misinterpreted the instructions *Turn right* and *Turn left* (71.43% and 81.82% were recognized). They also had difficulty in differentiating between *Flex the legs* and *Stretch the legs* (83.33% and 87.80% were recognized). Overall, four volunteers misinterpreted the instructions of category C1, two misinterpreted C2, three misinterpreted C3, and six misinterpreted C5 (see Table 6.4 for categories).

Tactile instructions lead to faster verbal response times.

On average, the difference between the time stamps when an applied instruction ended and the time stamps when the participants started to utter

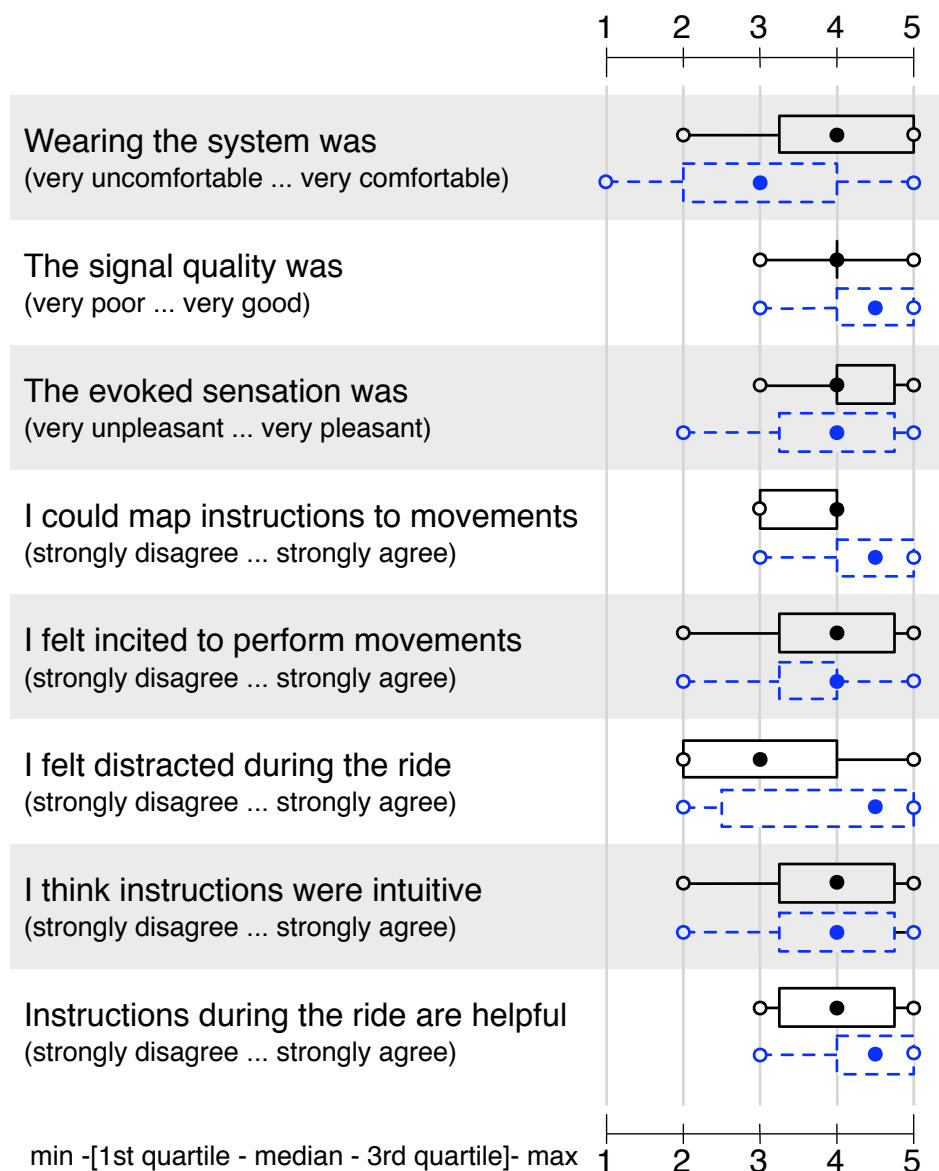


Figure 6.13: Likert scale ratings of tactile instructions (continuous, black) and of verbal instructions (dashed, blue).

a response was lower for the tactile channel ($M = 1.01$ sec, $SE = 0.16$ sec) than for the audio channel ($M = 1.98$ sec, $SE = 0.14$ sec). This difference was significant $t(9) = 6.30, p < 0.01$ and did represent a large effect $r = 0.90$.

Fig. 6.13 shows the answers to the questionnaire, regarding the two experimental conditions. Some participants did not like to wear the standard Nokia N70 earplugs used during the study because they were big and uncomfortable. Both tactile and spoken instructions were good to perceive, but one participant felt disturbed by spoken instructions. In general, the tactile sensations were pleasant. Neither modality was superior in intuitively representing body movements or in inciting the participants to per-

Both tactile and audio instructions were considered useful during descents.

form these movements. On average, however, tactile instructions were rated as being slightly less distracting than spoken instructions. Overall, both modalities were considered useful for providing feedback during descents.

Spoken instructions were easier to interpret and could be repeat word for word.

For question four, which addressed how well the participants could map instructions to movements, a Wilcoxon signed-rank test revealed that spoken instructions were rated significantly higher ($Mdn = 4.5$) than tactile instructions ($Mdn = 4$), $T = 0, n = 7, p = .011, r = -.13$. Overall, six participants stated that spoken instructions were easier to interpret. In particular, these instructions were simply repeated word for word. This was not the case with tactile instructions, which required additional cognitive effort for translating the perceived stimuli into words. Even so, the other four participants (three women, two advanced beginners, two advanced riders) preferred tactile instructions; these commands were subtler, less annoying, and less stressfully to wait for. Also, the external noises while descending the slope did not interfere with the tactile stimuli.

Three participants preferred the pull metaphor.

Three volunteers commented that the mapping between the tactile patterns and their meaning was less obvious. They expected to move towards the vibration, as would be the case for instructions based on the pull metaphor. Even so, they did not have difficulty in learning the chosen mapping.

Directional lines were easy to localize, but their direction was difficult to notice.

All participants stated that they could clearly identify the locations where the tactile stimuli were applied to the body. When asked whether they could recognize the direction that the patterns displayed on the skin, the experienced snowboarders stated that they could perceive these directions. Even so, the less skilled snowboarders stated that they did not recognize the direction. Also, the rotational patterns were perceived as localized taps and less as continuous movement. This sensation made it difficult to recognize in which direction to turn. Overall, the intensity of the stimuli felt weaker during the ride compared to the learning phase while standing still. Four participants suggested that we should increase the intensity of the vibration, which could make the tactile patterns easier to perceive.

Additional comments

To increase the vibration intensity, two participants proposed to activate neighboring actuators simultaneously instead of sequentially. One participant suggested larger sensations across the body. For example, stimuli that started at the thighs and that ended at the torso could indicate *Stretch the legs*. Two participants did not like to wear the backpack with boxes and further suggested to remove the wires in future systems.

The experimenter observed movements during descents.

The experimenter descended together with the participants to observe if they performed the movements as requested. Although she did not know when the system triggered an instruction nor which instruction this was, she observed movements that obviously originated from the randomly delivered instructions. One participant fell twice and explained that she had tried hard to shift her weight towards the tail of the snowboard upon perceiving the instruction *Lean towards the tail* (in fact, this movement can lead to falls, as it is a common mistake in snowboarding, see section 4.2). The two proficient snowboarders commented that they were annoyed to execute

instructions at inappropriate times. Since these instructions often interfered with their riding technique, they did not move as requested.

Overall, the wearable platform worked reliably on the slope, but the mobile phone that recorded the utterances stopped working during three descents. These descents were repeated.

Discussion

The findings of this study provided the first estimate on the perception and interpretation of tactile motion instructions under real-world conditions. Overall, neither the ability to perceive nor the ability to interpret these instructions did severely degrade compared to the laboratory study. A few instructions were missed (3.81%), yet we cannot state if the participants did not perceive the stimuli or if they were too distracted to answer. Regarding the profile of the instructions, the average correct score measured on the slope ($M = 87.06\%$, $SD = 8.03\%$) was slightly lower than the score measured on the Wii balance board for participants who were new to these tactile stimuli (group A: $M = 91.67\%$, $SD = 2.90\%$) (see section 6.3.1).

The patterns that represented upper body rotation were most often misinterpreted, as was also the case on the Wii balance board. The modified patterns that were delivered around the waist were perceived, but they were still too difficult to differentiate. In particular, the less skilled snowboarders did not notice the direction that these patterns displayed on the skin. For this reason, these rotational patterns were inappropriate as tactile instructions. They should be replaced with stimuli that can be discriminated.

Four participants misinterpreted the instructions *Stretch (flex) the legs*, although these tactile patterns were delivered to opposing body sites. This indicates that some users might benefit from longer training in order to learn the meaning of these stimuli. In particular, the directional line at the front of the thighs might be less obvious as instruction, as this pattern was seldom associated with *Stretch the legs* in the initial study (see section 6.2).

Spoken instructions were superior to tactile instructions regarding their perception and interpretation. Also, six participants preferred spoken instructions, stating that they could better map these messages to body movements. Even so, the high recognition accuracy of tactile instructions and the answers to the questionnaire indicate that tactile instructions could replace spoken instructions. Moreover, four participants preferred tactile instructions, stating that these instructions were less distracting and easier to perceive in the noisy environment. Other aspects between spoken and tactile instructions did not significantly differ. Regarding comfort, distraction, and intuitiveness, the ratings were similar but revealed a slight preference for tactile instructions. For these reasons, users should have the option to choose over which modality to receive instructions.

The ability to recognize instructions on the slope was slightly lower than on the Wii balance board in the laboratory.

Rotational patterns around the waist are inappropriate as instructions.

Longer training sessions for learning the meaning of some tactile patterns

Tactile instructions can replace spoken instructions.

The vibration location quickly conveyed the meaning of the stimuli.

Tactile instructions lead to faster verbal response times than spoken instructions. This faster response time is an advantage for sports that require quick reactions. We assume that the participants started to interpret tactile instructions as soon as they noticed vibration at a specific body site, which characterized these unique patterns. In contrast, spoken instructions required the participants to listen to the whole utterances in order to perceive the meaning of these messages.

The experimental conditions probably degraded the ability to name the instructions.

Although our findings indicate that tactile instructions could be applied during physical activities, several factors likely influenced the participants' responses and probably increased the number of mistakes, as was also the case on the Wii balance board (see section 6.3.1). The instructions were randomly applied and also occurred at inappropriate times when corrections were not required or when they could have interfered with the rider's movements. A few participants indicated that they expected to move towards the vibration instead of away. Moreover, the participants responded verbally, which increased their cognitive workload and which could have caused some of them to mix up the directions. Also, the training session for learning the instructions before descending the slope was short. Another issue was that our custom-tailored tactile suit apparently prevented the motors from directly touching the skin along the sternum, which could explain why the instruction *Lean backward* was missed a few times.

6.3.3 Perception under Real-World Conditions: Horseback Riding

The first study that we have conducted to investigate if tactile motion instructions could be perceived and recognized during a demanding physical activity under real-world conditions focused on snowboarding. To broaden the basis for designing tactile instructions, we have conducted another field study with equestrians. This study took place at the same time as the field study with snowboarders and was conducted by Hilgers [2008] under the guidance of the author.

The correct posture for sitting in the saddle and typical riding mistakes

Equestrians have to maintain a straight vertical line between the head, the shoulders, the hip, and the heels; the back is straight, the shoulders are square, and the knees are slightly bent (see Fig. 6.14). This posture can challenge beginners. Inexperienced riders tend to lean the upper body forward or backward, or they move the shoulders forward. While riding in the ring, they tend to lean their torso towards the center of the ring. These movements shift the center of gravity to a position that makes it difficult for the rider and for the horse to ride without getting tired or sore. Also, many beginners keep their legs forward as if they sat on a chair, or they point their toes outward. In this posture, they lose the contact between the thighs and the horse such that they cannot guide the animal.

The instruction set for correcting wrong posture

To correct these mistakes, many of the body movements listed in Table 6.4 could be applied as instructions. For this reason, we decided to focus



Figure 6.14: Horseback riders have to maintain a balanced and secure posture in the saddle.

on these movements, except for upper body rotation. The instructions WL and WR, which originally prompted to shift the weight to the left or right foot, were reworded to represent *Shift the weight to the left (right)*. These new instructions were similar to LL and LR, which prompted to lean sideways. Furthermore, we introduced an alternative instruction that signaled *Pull the shoulders back* (PBS). This instruction simultaneously pulsed actuators at the upper chest, which were located directly below the clavicles: $PSB = P^3(SLV) + P^3(SRV)$ (see Fig. 6.3 for the acronyms on body location).

Participants and Hardware Setup

Eight equestriennes aged 12–37 years ($M = 22.1$ years) were recruited from a local horse-riding club. On a scale ranging from level 1 (beginner) to level 5 (expert), three participants rated their riding skills as level 2 (advanced beginner), one as level 3 (advanced), and four as level 4 (proficient). They weekly practiced horse riding.

All participants wore the custom tactile suit with the vibration motors over their standard riding dress. Similar to the study on the slope, a backpack stored three SensAct boxes during the ride (see Fig. 6.14). A Nokia N70 mobile phone controlled these boxes. Another mobile phone recorded the participants' utterances during the ride with a microphone that was attached to the rider's T-shirt.

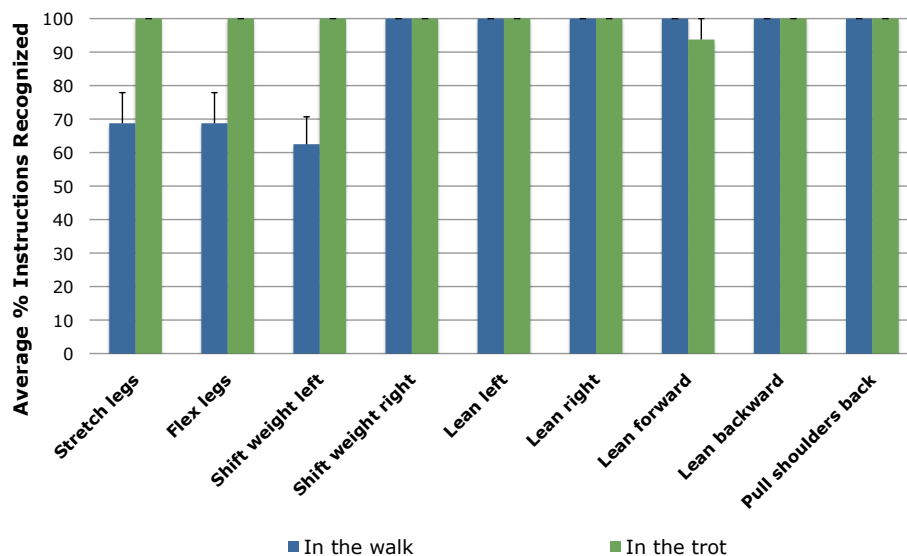


Figure 6.15: Average percentage of recognized instructions while riding a horse (with standard error). Some instructions were misinterpreted at the beginning while riding at walk but not subsequently while riding at trot.

Experimental Setup

The experiment took place in an outdoor riding ring.

An outdoor riding ring served as location for conducting the experiment. This riding ring was also used by other riders while the study took place. After mounting the horse, the participants learned the meaning of the tactile instructions. Therefore, the experimenter manually triggered the patterns and explained which body movements they represented. She repeated instructions on request until the participants were sure to have memorized their meaning. The instruction set for the upper and lower body were tested separately. Their order was counterbalanced across the participants.

The participants uttered the instructions and performed the movements.

The participants' task was to ride the horse in a balanced position at walk. Subsequently, they had to increase the speed for riding at trot. For these two gaits, the host device was programmed to deliver instructions with a random delay of 5–10 seconds and to apply each instruction twice in random order. The participants' task was to say out aloud which instruction they perceived and to perform the corresponding movement. After the experiment, they answered a questionnaire asking their view on tactile motion instructions (see Appendix C).

Results

The participants did not miss but misinterpreted a few instructions.

Fig. 6.15 depicts the profile of the recognized instructions. On average, the participants recognized 88.89% (SD = 16.76%) of the instructions in the walk and 99.31% (SD = 2.08%) in the trot. Although all instructions were perceived, six riders misinterpreted the instructions that were applied

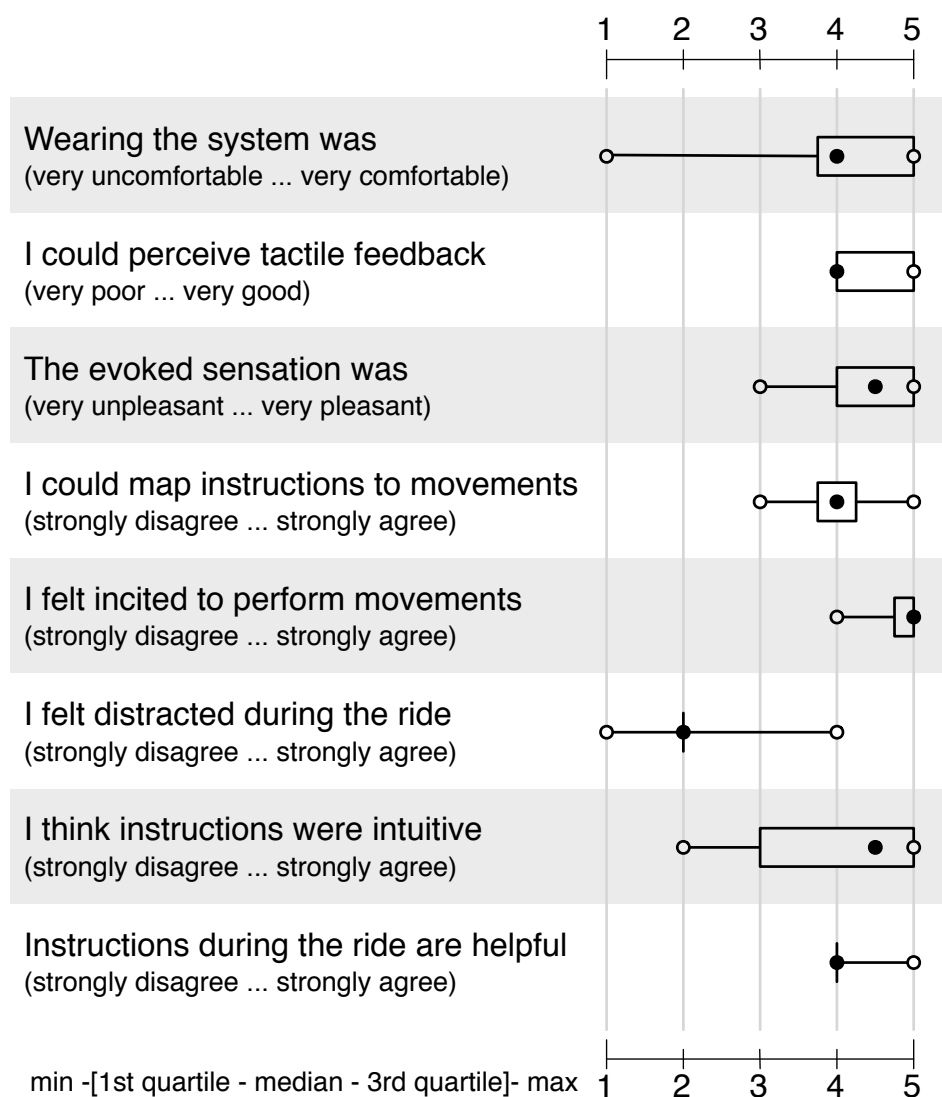


Figure 6.16: Likert scale ratings of tactile instructions while riding a horse.

to the thighs while riding at walk: two advanced beginners, one advanced rider, and two proficient riders misinterpreted once the instructions *Stretch the legs*, *Flex the legs*, and *Shift the weight to the left*; one proficient rider once misinterpreted *Shift the weight to the left*. Another proficient rider once misinterpreted *Lean forward* while riding at trot.

Fig. 6.16 shows the answers to the questionnaire. All participants disliked wearing the backpack, but the tight-fitting clothes with the motors did not cause discomfort. The instructions were good to perceive, and the evoked sensation were pleasant. All participants could map the instructions to movements and felt incited to perform these movements. Although seven participants stated that the instructions intuitively represented the chosen body movements, the instruction set for the upper body was preferred, whereas lower body instructions did not seem to clearly convey their

Tactile motion instructions could be useful during training.

message. Overall, the participants uniformly agreed that if future wearable systems could detect all riding mistakes, these instructions could help them to learn how to ride with correct posture. One proficient rider, however, felt distracted by these instructions because they shifted her focus too much away from the horse to her own posture.

New suggestions for tactile instructions

During debriefing, one participant suggested that we should change the meaning of the tactile stimuli that were delivered to the thighs. Directional lines in upward or downward direction at the back of the thighs should represent *Stretch the legs* or *Flex the legs*. While lateral stimuli at the torso could indicate *Lean left* and *Lean right*, lateral stimuli at the thighs should signal *Press the thighs together* for increasing the contact to the horse.

Stimuli along the spine and sternum were barely noticed.

The more experienced riders stated that they could recognize the direction that the tactile patterns displayed on the skin. In contrast, the less experienced riders stated that they did not pay attention to the characteristics of the stimuli during the ride. Moreover, the stimuli that were rendered along the spine and sternal were more difficult to notice because the body anatomy and the riding dress beneath the tactile suit prevented the motors from contacting the skin.

Discussion

All instructions were recognized, but lower body patterns need a different mapping.

The findings of this study indicate that young horse riders did not have difficulty in perceiving and recognizing tactile motion instructions. Moreover, they did not miss instructions, as was the case on the slope. Even so, the lower body instructions *Stretch (flex) the legs* and *Shift the weight to the left* were more often misinterpreted than on the Wii balance board (see Fig. 6.9 and Fig. 6.10) or while snowboarding (see Fig. 6.12). This indicates that for this sport, which required to sit in a saddle, the mapping between these patterns and their meaning was not obvious. In fact, one participant proposed alternative mappings that could be more appropriate for the chosen lower body patterns.

We observed a learning effect after riding at walk.

The participants first rode at walk and subsequently at trot. Since the order of these riding gaits was not counterbalanced, a learning effect could be observed. Lower body instructions were misinterpreted at the beginning while riding at walk but not while riding at trot. Obviously, riding at walk served as additional learning phase and helped the participants to remember the meaning of these patterns.

Verbal responses did not cause misinterpretations when riding at trot.

Riding at trot is physically and cognitively more demanding than riding at walk. Even so, only one participant misinterpreted an instruction while riding at trot. For this reason, we assume that responding verbally was less challenging while horseback riding than while snowboarding. This indicates that responding verbally is one reason that could have caused misinterpretation while snowboarding (see section 6.3.2).

Overall, all participants advocated tactile motion instructions during the ride, stating that equestriennes usually try to improve the gait of their horses and often practice different figures in the riding ring. A wearable system that could automatically provide hints for corrections could remind them to also pay more attention to their own posture during training. Nevertheless, one participant felt distracted by the tactile stimuli. This indicates that the tactile channel might not always be appropriate for providing instructions during training.

6.3.4 Revised Design Recommendations

Based on the findings of the studies that we have conducted under real-world conditions, we can revise our first guidelines for designing tactile motion instruction patterns (see section 6.2.4). Initially, we have proposed directional lines based on sensory saltation for communicating the direction in which to perform body movements. While some skilled participants could pay attention both to the sport and to the characteristics of these stimuli, the less skilled participants could not identify the direction of these lines. In particular, the rotation around the waist was difficult to discriminate. For this reason, directional lines should not be used as primary parameter for encoding the direction in which to move the body.

The direction of lines can be difficult to identify.

Instead, body location should be used as primary parameter for communicating the meaning of an instruction. If all instructions are delivered to distinct locations, they will be unique and will not require the user to pay attention to other characteristics of the stimuli. Nevertheless, directional lines could serve as secondary parameter for encoding information redundantly, and for intensifying the sensory experience.

Body location as primary encoding parameter

We also found that our tactile suit prevented the motors from touching the skin along the spine and sternum such that tactile stimuli delivered to these locations were more difficult to perceive. Moreover, some of these tactile patterns were missed while snowboarding (see section 6.3.2). For this reason, other body locations should be used for representing *Lean forward* and *Lean backward*. The upper back and the upper chest could be possible candidates, as localized pulses applied to the shoulder blades and directly below the clavicles were always perceived while snowboarding and while riding a horse.

Alternative body locations and patterns for tactile instructions

Moreover, the directional lines that were rendered around the waist have to be substituted with distinct stimuli that can be discriminated in active situations. Therefore, in the next section, we will explore which alternative body locations and tactile patterns could be more appropriate for representing the instructions *Turn left* and *Turn right*.

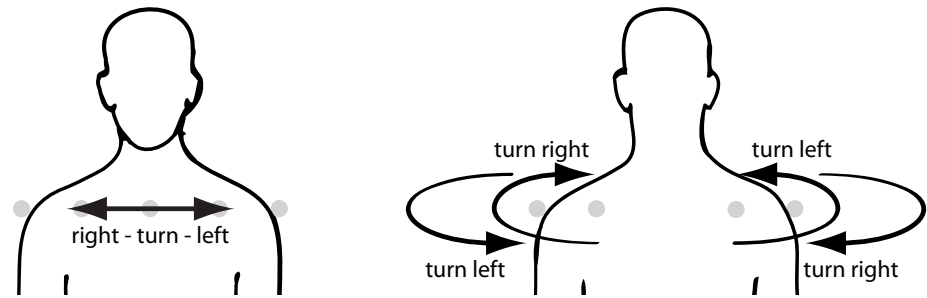


Figure 6.17: Some alternative body locations and tactile patterns that could represent upper body rotation.

6.4 Instructions for Upper Body Rotation

Alternative patterns for upper body rotation

Our studies have revealed that directional lines around the waist, which signaled *Turn left (right)*, could not be accurately differentiated in active situations (see section 6.3.1 and 6.3.2). Since these patterns shared all actuators, our participants had to pay attention to identify in which direction the pulses moved on the skin. In this section, we will present alternative body locations and tactile patterns that could represent these instructions.

Semicircular lines around the shoulders could extend localized pulses.

Initially, we have reported that our volunteers who participated in the study on the intuitive interpretation of tactile stimuli did not associate localized pulses delivered laterally to the shoulders as request to turn to the left or to the right (see section 6.2). Although similar stimuli have been applied as instructions in navigation systems (see section 5.4.2) because they can intuitively represent spatial direction relative to the position of the body [van Erp, 2005], in our case, they were inexpressive and were not associated with turning around. We have also noted that our participants preferred directional lines to localized pulses because lines provided additional information how to move. For these reasons, we considered a semicircular line around the shoulder for balancing the need for expressive stimuli that could intuitively prompt to turn around and for unique stimuli that users could discriminate in active situations based on the location of the vibration. These tactile patterns would resemble localized pulses but would also move around the shoulder to indicate in which direction to turn.

We compared different patterns that could prompt to turn around.

We conducted a study to investigate how potential users would rate these semicircular lines around a single shoulder for representing *Turn left* and *Turn right* in a stationary situation. A directional line applied around both shoulders and a horizontal line applied to the chest were considered as reference patterns. We expected that rotation around both shoulders would be preferred because this pattern was often associated with *Turn left (right)* when delivered around the waist (see section 6.2). Also, we expected that the horizontal line delivered to the chest would be preferred least, as this pattern could be interpreted differently, such as to lean sideways.

Table 6.8: Tactile patterns that could represent *Turn left* (TL_x) and *Turn right* (TR_x), as depicted in Fig. 6.17 (see Table 6.1 and Fig. 6.3 for the acronyms on the location of these stimuli).

| Acronym | Duration (seconds) | Tactile pattern |
|---------|--------------------|--|
| TL_1 | 0.4 | $P(SLV) \rightarrow P(SLL) \rightarrow P(SLD)$ |
| TL_2 | 0.4 | $P(SRD) \rightarrow P(SRL) \rightarrow P(SRV)$ |
| TL_3 | 1.3 | $P^3(SLV) \rightarrow P^3(SLL) \rightarrow P^3(SLD)$ |
| TL_4 | 1.3 | $P^3(SRD) \rightarrow P^3(SRL) \rightarrow P^3(SRV)$ |
| TL_5 | 0.85 | $TL_1 \rightarrow TL_2$ |
| TL_6 | 2.65 | $TL_3 \rightarrow TL_4$ |
| TL_7 | 1.75 | $TL_5 \rightarrow TL_5$ |
| TL_8 | 1.3 | $P^3(SRV) \rightarrow P^3(BMV) \rightarrow P^3(SLV)$ |
| TR_1 | 0.4 | $P(SRV) \rightarrow P(SRL) \rightarrow P(SRD)$ |
| TR_2 | 0.4 | $P(SLD) \rightarrow P(SLL) \rightarrow P(SLV)$ |
| TR_3 | 1.3 | $P^3(SRV) \rightarrow P^3(SRL) \rightarrow P^3(SRD)$ |
| TR_4 | 1.3 | $P^3(SLD) \rightarrow P^3(SLL) \rightarrow P^3(SLV)$ |
| TR_5 | 0.85 | $TR_1 \rightarrow TR_2$ |
| TR_6 | 2.65 | $TR_3 \rightarrow TR_4$ |
| TR_7 | 1.75 | $TR_5 \rightarrow TR_5$ |
| TR_8 | 1.3 | $P^3(SLV) \rightarrow P^3(BMV) \rightarrow P^3(SRV)$ |

Fig. 6.17 illustrates the sensations that these patterns evoked. Table 6.8 lists the corresponding stimuli and their duration based on the standard timing parameters ($BD = 100$ ms, $IBI = 50$ ms, see Fig. 6.2). To experiment with different sensations, we varied the length of these patterns with stimuli that pulsed the motors either once (P) or for three times (P^3) (see section 6.1.4 for the notation). With one pulse per motor, these stimuli exploited the effect of apparent movement, whereas three pulses exploited the sensory saltation phenomenon (see section 5.3). Note that TL_1 , TL_3 , TR_1 , and TR_3 started at the chest, moved along the shoulder, and ended at the back. TL_2 , TL_4 , TR_2 , and TR_4 were reversed—they started at the back and ended at the chest. TL_5 , TL_6 , and TL_7 , and their counterparts TR_5 , TR_6 , and TR_7 , resembled the original patterns that were delivered around the waist. TL_8 and TR_8 rendered horizontal lines to the upper chest.

The tactile patterns based on apparent movement or on sensory saltation.

6.4.1 Participants

Ten volunteers aged 21–27 years ($M = 24.1$ years, three women) were recruited from the local university. Two candidates had participated in the first experiment on the intuitive interpretation of tactile stimuli (see section 6.2). One candidate had participated in the laboratory study on the Wii balance board (see section 6.3.1). None of them reported problems in perceiving tactile stimuli. All participants occasionally practiced sport, including jogging and fitness exercises.

6.4.2 Experimental Setup

Two SensAct boxes (see section 3.1.1) were used. These were placed on a table such that carrying a backpack was not necessary. The participants stood upright and listened to soft music played back through headphones, which blocked the auditory cues from the vibrating motors. The experimenter first triggered all patterns once in random order to familiarize the participants with the artificial tactile sensations.

The patterns were tested in pairs.

The patterns listed in Table 6.8 were triggered in pairs of two for turning left (TL_x, TL_y) or for turning right (TR_x, TR_y), $1 \leq x, y \leq 8, x \neq y$. Since testing all combinations was too time-consuming, we chose the following pattern sets in order to compare the key characteristics of the tactile patterns, while limiting the experimental time to one hour for each participant.

- $A = \{(TL_1, TL_3), (TR_1, TR_3)\}$: Patterns around one shoulder, starting at the chest and ending at the back, based on single pulses (TL_1, TR_1) vs. triple pulses per motor (TL_3, TR_3).
- $B = \{(TL_2, TL_4), (TR_2, TR_4)\}$: Patterns around one shoulder, starting at the back and ending at the chest, based on single pulses (TL_2, TR_2) vs. triple pulses per motor (TL_4, TR_4).
- $C = \{(TL_5, TL_6), (TR_5, TR_6)\}$: Patterns around both shoulders, starting at the chest, based on single pulses (TL_5, TR_5) vs. triple pulses per motor (TL_6, TR_6).
- $D = \{(TL_1, TL_5), (TR_1, TR_5)\}$: Patterns with single pulses per motor delivered around one shoulder (TL_1, TR_1) vs. around both shoulders (TL_5, TR_5).
- $E = \{(TL_5, TL_7), (TR_5, TR_7)\}$: Patterns with single pulses per motor delivered once around both shoulders (TL_5, TR_5) vs. twice around both shoulders (TL_7, TR_7).
- $F = \{(TL_1, TL_8), (TR_1, TR_8)\}$: Patterns with single pulses per motor around one shoulder (TL_1, TR_1) vs. patterns with triple pulses per motor at the chest (TL_8, TR_8).
- $G = \{(TL_3, TL_8), (TR_3, TR_8)\}$: Patterns with triple pulses per motor around one shoulder (TL_3, TR_3) vs. patterns with triple pulses per motor at the chest (TL_8, TR_8).

Forced-choice paradigm for answers

The experimenter used the SensAct Control application (see Fig. 3.9) to randomly trigger the tactile patterns. All fourteen pairs were applied twice. The order of the pairs and the order of the patterns within each pair were counterbalanced across the participants. The delay between two patterns within a pair was three seconds. For each pair (TL_x, TL_y) or (TR_x, TR_y), the participants stated the direction in which they would turn and which pattern they preferred, based on *forced-choice paradigm*.

Table 6.9: The preferred tactile patterns (in %) that could represent *Turn left* and *Turn right* (see Table 6.8).

| Pattern set | Turn left | | Turn right | |
|-------------|--------------|--------------|--------------|--------------|
| | TL_x | TL_y | TR_x | TR_y |
| <i>A</i> | TL_1 (40%) | TL_3 (60%) | TR_1 (75%) | TR_3 (25%) |
| <i>B</i> | TL_2 (75%) | TL_4 (25%) | TR_2 (40%) | TR_4 (60%) |
| <i>C</i> | TL_5 (75%) | TL_6 (25%) | TR_5 (60%) | TR_6 (40%) |
| <i>D</i> | TL_1 (30%) | TL_5 (70%) | TR_1 (45%) | TR_5 (55%) |
| <i>E</i> | TL_5 (85%) | TL_7 (15%) | TR_5 (80%) | TR_7 (20%) |
| <i>F</i> | TL_1 (80%) | TL_8 (20%) | TR_1 (85%) | TR_8 (15%) |
| <i>G</i> | TL_3 (80%) | TL_8 (20%) | TR_3 (80%) | TR_8 (20%) |

6.4.3 Results

The participants uniformly considered the direction of the patterns for their responses and turned in the direction in which the patterns moved on the skin. For example, TL_2 was associated with *Turn left*, although this pattern moved from the back to the chest around the right shoulder. Table 6.9 summarizes the percentage of responses to the patterns. A Wilcoxon signed-rank test revealed that for set *E*, the participants significantly preferred more often TL_5 , which ran once around both shoulders ($Mdn = 2.0$), than TL_7 , which applied TL_5 twice around both shoulders ($Mdn = 0$), $T = 5, n = 9, p = 0.02, r = -.12$. Also, for set *F*, they significantly preferred more often the pattern TR_1 , which applied single pulses around the right shoulder ($Mdn = 2.0$), than TR_8 , which applied triple pulses to the chest ($Mdn = 0$), $T = 5, n = 9, p = 0.02, r = -.12$.

The differences between the number of times that the patterns of the other pairs were chosen were not significant, but the answers indicated which patterns were preferred. On average, in set *C*, patterns with single pulses around both shoulders (TL_5, TR_5) were slightly favored over patterns with triple pulses around both shoulders (TL_6, TR_6). Surprisingly, the preference for patterns with single or triple pulses around one shoulder varied (sets *A* and *B*): at the right shoulder, single pulses (TL_2, TR_1) were preferred to triple pulses (TL_4, TR_3); at the left shoulder, triple pulses (TL_3, TR_4) were slightly preferred to single pulses (TL_1, TR_2). In set *D*, patterns around both shoulders (TL_5, TR_5) were slightly favored over those around one shoulder (TL_1, TR_1). In set *G*, patterns around one shoulder (TL_3, TR_3) were favored over those at the chest (TL_8, TR_8). Overall, this indicates that patterns with single pulses (*P*) and rotation around both shoulders were slightly preferred as instructions.

Debriefing revealed that six participants initially interpreted rotation around both shoulders (TL_5 and TL_6 in sets *C* and *D*) and the corresponding counter-patterns (TR_5 and TR_6) as request to turn the whole body around 180° . Three of these participants stated that two rotations around both shoulders (TL_7 and TR_7 in set *E*) enticed to turn around

The direction of the stimuli on the skin prevailed over their location on the body.

Patterns with single pulses and rotation around both shoulders were preferred.

The stimulus characteristics influenced the responses.

360°. In contrast, the patterns that stimulated only one shoulder represented less extensive movements, such as turning the torso by 90°. Also, three participants stated that three sequential pulses per motor felt slower and thus seemed to request slower turns compared to patterns that based on a single pulse per motor. Regarding the patterns that were applied to the chest (TL_8 and TR_8 in sets F and G), three participants associated these stimuli with *Lean backward* or straighten up. Two other participants interpreted these patterns as *Lean forward*. Another participant looked in the direction that these patterns rendered along the chest.

6.4.4 Discussion

Rotation around both shoulders was favored.

The findings of this study supported our initial observations that we have reported on the intuitive interpretation of tactile stimuli (see section 6.2). First, directional lines can provide effective cues how to move the body if the direction of the stimuli can be identified. Second, the directional lines that were sequentially applied around both shoulders, which resembled rotation around the waist, were favored for representing *Turn left (right)*.

Rotation around one shoulder provides unique and expressive cues in which direction to turn.

Even so, the direction of rotation around both shoulders could be difficult to differentiate in active situations. For this reason, we propose as instructions the semicircular lines that were applied either around the left shoulder (TL_1, TL_3, TR_2, TR_4) or around the right shoulder (TL_2, TL_4, TR_1, TR_3). These patterns were unique because they did not share actuators. Although they were less often chosen than rotation around both shoulders, they were expressive because the participants followed the direction of these stimuli regardless of the shoulder that was stimulated. Nevertheless, as with the other instructions that based on directional lines, the body location should serve as primary parameter for encoding in which direction to turn. The displayed direction could serve as secondary parameter to redundantly encode the message and to intensify the evoked sensation.

Push and pull metaphors for upper body rotation.

We could describe the semicircular lines around a single shoulder to exploit the push metaphor or the pull metaphor. If these patterns were based on the push metaphor, they would stimulate the shoulder opposed to the turning direction, using stimuli that would run from the back to the chest, either around the right shoulder to signal a turn to the left (TL_2, TL_4), or around the left shoulder to signal a turn to the right (TR_2, TR_4). If they were based on the pull metaphor, they would stimulate the left shoulder to signal a turn to the left (TL_1, TL_3) and the right shoulder to signal a turn to the right (TR_1, TR_3), using pulses that would start at the chest and that would end at the back. Moreover, we could describe these patterns to exploit both metaphors simultaneously. For example, we could describe TL_2 delivered around the right shoulder to start with a push from the back towards the left and to conclude with a pull at the chest towards the left.

The number of pulses could encode how fast the body should be turned.

Overall, single pulses per motor were preferred over triple pulses, which felt slower on the skin. Some participants indicated that the duration of

these stimuli could encode how quick the body should be turned. While single pulses could indicate rapid turns (TL_1 , TR_1 , TL_2 and TR_2), triple pulses could indicate slower turns (TL_3 , TR_3 , TL_4 and TR_4). Even so, the duration of these patterns could be difficult to recognize in active situations, unless the user could pay attention to the characteristics of the stimuli.

The directional lines that were applied along the chest were inappropriate for representing upper body rotation. We assumed that they could prompt to lean sideways, but they were associated with leaning forward or backward, as was also the case with localized pulses that were applied to the chest (see section 6.2). These findings suggests that for the instructions *Lean forward (backward)*, localized pulses applied to the chest or the back could replace the directional lines delivered along the spine or sternum.

Pulses at the chest prompted to lean forward or backward.

6.5 Preliminary Design Recommendations

Based on our findings on the perception and interpretation of artificial tactile stimuli, we can highlight three issues that are relevant for designing tactile motion instruction patterns for active situations:

- Body location should be used as primary parameter for encoding which part of the body to move.
- To signal the direction in which to perform a movement, the mapping between a stimulus and its meaning could represent a push or a pull of the body.
- Directional lines can create expressive sensations and can intensify the tactile experience. These lines could be used as secondary parameter for encoding the direction in which to perform a movement.

We have selected those patterns as instructions that best represented body movements and that were unique and well perceivable in active situations. These patterns comprised the directional lines that were applied laterally to the torso and laterally to the thighs, to the front and to the back of the thighs, the semicircular directional lines that were applied around each shoulder, and the pulses that stimulated the upper chest and the upper back. Fig. 6.18 illustrates these patterns, considering the pull metaphor, which would prompt to move towards the vibration.

The revised set of tactile motion instruction patterns

Directional lines in upward direction laterally to the torso and laterally to the thighs could be described to represent the progressively increasing bending radius of the body when leaning sideways or when shifting the weight to one foot (see section 6.2.4). This description would be appropriate for the pull and push metaphor. For the pull metaphor, however, directional lines that proceed downward could be described to pull the torso or to pull the weight downward towards the same side where the vibration occurs (see

Directional lines in upward or downward direction

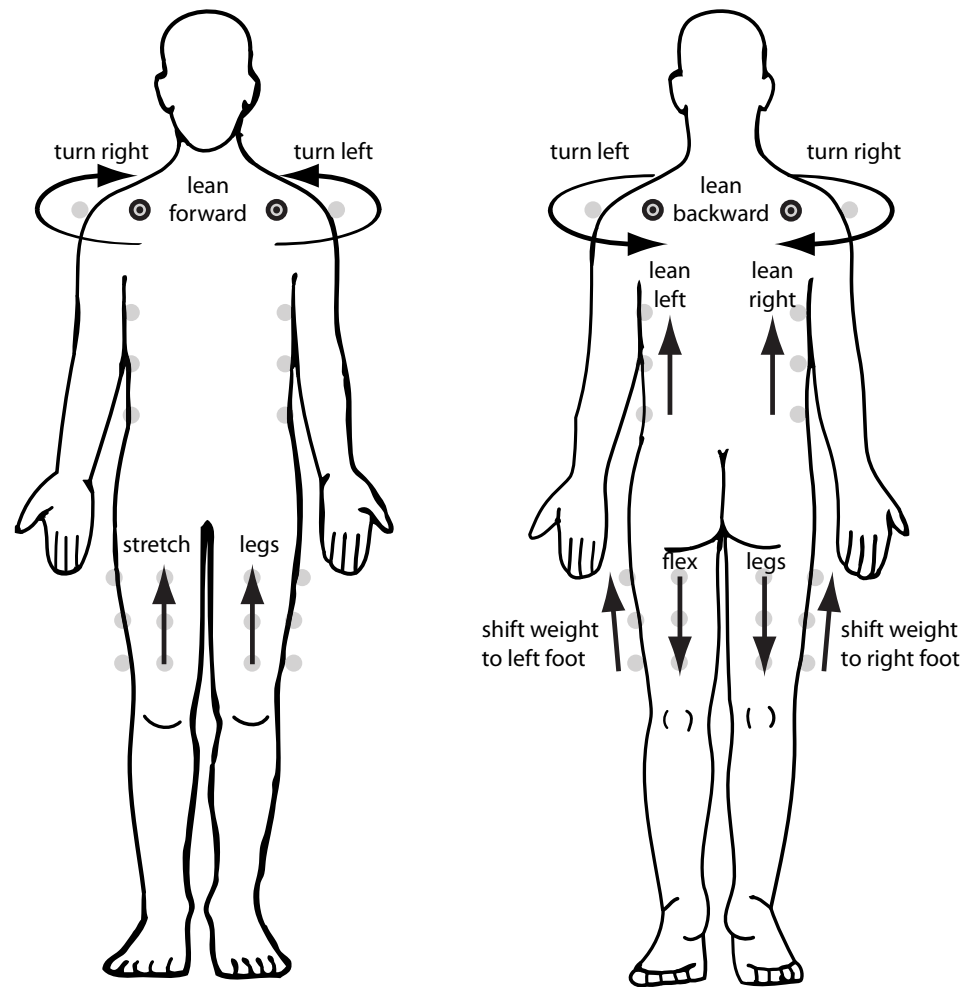


Figure 6.18: The revised set of tactile patterns, based on stimuli that could be described to pull the body in the direction in which to perform the movements. Directional lines delivered laterally to the torso and to the thighs could indicate the progressively increasing bending radius of the body when leaning sideways. The double-circles at the chest and back represent the localized sensations for the instructions *lean forward* (*backward*).

Fig. 6.19). Even so, this description seems to be less appropriate for the push metaphor because the user would move in the opposite direction that these lines would indicate. Moreover, the direction of these lines could be difficult to recognize in active situations such that their actual direction would be less important in this case.

For the composed tactile motion instruction patterns, the duration of the localized pulses is 400 ms. The duration of the directional lines is 1300 ms (see Fig. 6.2). The formal notation for these patterns is (see section 6.1.4 for the notation, Fig. 6.3 for the acronyms on body location, and Table 6.4 for the acronyms on body movements):

Stretch the legs, flex the legs:

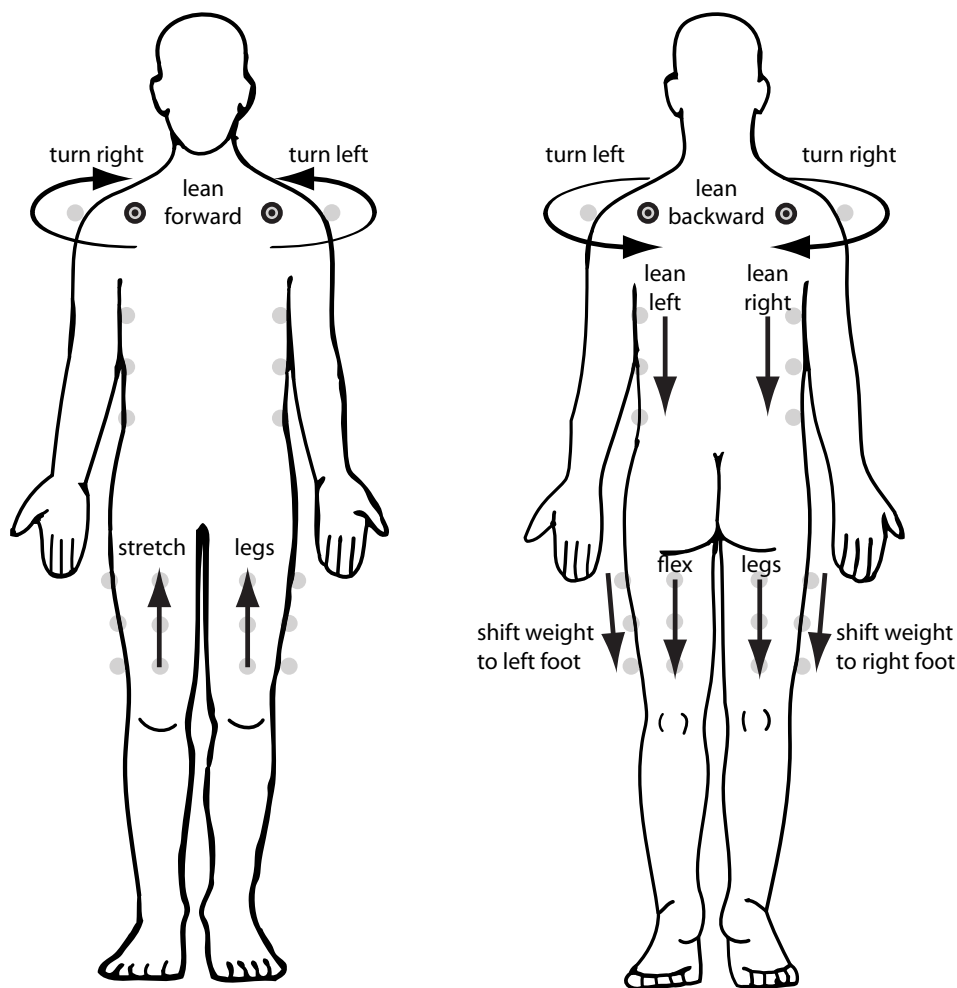


Figure 6.19: For the pull metaphor, directional lines delivered in downward direction laterally to the torso and to the thighs could alternatively indicate the direction to lean, thereby pulling the body downward when leaning sideways (compare to Fig. 6.18).

- $SL = R_U(TRV) + R_U(TLV)$ at the front of the thighs
- $FL = R_D(TRD) + R_D(TLD)$ at the back of the thighs

Shift the weight to the left / right foot:

- $WL = R_U(TLL)$ laterally at the left thigh
- $WR = R_U(TRL)$ laterally at the right thigh

Lean upper body to the left / right:

- $LL = R_U(BLL)$ laterally at the left side of the torso

- $LR = R_U(BRL)$ laterally at the right side of the torso

Lean upper body forward / backward:

- $LF = P^3(SLV) + P^3(SRV)$ at the upper chest
- $LB = P^3(SLD) + P^3(SRD)$ at the upper back

Turn upper body to the left / right:

- $TL = P^3(SLV) \rightarrow P^3(SLL) \rightarrow P^3(SLD)$ around the left shoulder
- $TR = P^3(SRV) \rightarrow P^3(SRL) \rightarrow P^3(SRD)$ around the right shoulder

6.6 Closing Remarks

In this chapter, we have focused on finding artificial tactile stimuli that could represent body movements in an intuitive way. Initially, we have observed how young adults interpreted localized pulses and directional lines that were applied to various body locations, and which body movements they performed. Based on the most frequent responses that were associated with the same body movements, we have composed tactile patterns that could be used as instructions for physical activities. We have called these patterns *tactile motion instructions*.

To iteratively refine these patterns and to evaluate if they could be perceived and their meaning recognized in active situations, we have focused on snowboarding and on horseback riding as example activities. We chose snowboarding because this sport allowed us to estimate how appropriate the designed tactile patterns would be as realtime instructions for physical activities that were physically and cognitively demanding. Overall, we have found that young adults were able to perceive and to identify these patterns with high accuracy. We have also found that tactile instructions lead to faster response times than spoken instructions. Moreover, about half of our study participants preferred tactile instructions to spoken instructions while descending the slope. These findings indicate that tactile motion instructions could be applied for correcting wrong posture during physical activities, in particular when the audio channel would be less appropriate for providing feedback on performance.

Even so, we have found that several participants sometimes misinterpreted tactile motion instructions in active situations. These mistakes were probably caused by the experimental conditions. The instructions were randomly triggered and could occur at inappropriate times when corrections were not required or when they did not match to the movements that the

participants already had to perform during the activity. Moreover, some participants mixed up the responses because they had difficulty in expressing the meaning of the patterns in words while moving the body. Also, a few participants learned to move away from the location where the vibration occurred, although they intuitively preferred to move towards the vibration. For these reasons, the results reported in this chapter should be regarded as first estimate on the perception of tactile motion instructions.

The findings of our studies have lead to a set of guidelines for designing tactile motion instruction patterns. In the next chapter, we will further evaluate these recommendations, in particular for instructions that could be described to push or to pull the body. Moreover, we will investigate how accurately sequences of instructions can be perceived and interpreted in active situations. Such sequences of tactile instructions could form a language that conveys longer messages, similar to words that form sentences in spoken languages.

Chapter 7

A Language of Tactile Motion Instructions

“I speak two languages, Body and English.”

—Mae West

In the previous chapter, we have introduced tactile patterns as instructions how to move the body. These patterns were based on the intuitive interpretation of young adults to artificial tactile stimuli. We have also reported several user studies that have shown that young adults could perceive and identify these tactile patterns with high accuracy in active situations.

In this chapter, we will focus on the language aspect of tactile motion instructions. While a single instruction could indicate when and how to move, a series of instructions could indicate the timing and the order of a sequence of movements. Such a sequence of tactile motion instructions would resemble a sequence of words that form sentences in spoken languages. They could guide the athlete through motion sequences that are difficult to learn, in particular those that involve various body movements that have to be coordinated in a specific order. For example, dancers have to move in accordance with the music and their partners. Dance beginners typically cannot execute all movements as required—they focus on one aspect that challenges them and often forget the complete motion sequence.

Another topic of this chapter is the encoding metaphor, regarding stimuli that either push or pull the body towards a direction. We have investigated how these opposing mappings between a stimulus and its meaning influenced the ability to identify tactile motion instructions depending on the user’s preference to being pushed or pulled. Also, we have re-evaluated which body movements young adults intuitively associated with the chosen tactile patterns and how well they could learn and recall in the long term the meaning that we have assigned to these patterns. These findings provided additional insights into the characteristics of tactile motion instructions and allowed us to estimate how general the composed instructions were.

A tactile language for physical activities could teach sequences of body movements.

Push vs. pull metaphor and intuitive interpretation

The remaining of this chapter is organized as follows:

- Section 7.1 discusses the concept of languages and reviews related work on tactile languages. We will highlight similarities and differences between our tactile language, which focused on physical activities, and tactile languages for other application domains.
- Section 7.2 describes a study that focused on the perception of single and compound instructions in a static and an active situation, considering the push and pull encoding metaphor.
- Section 7.3 describes a study that re-evaluated how appropriate the composed tactile patterns were for representing body movements.

7.1 Tactile Languages

A language is a method of communication.

The term *language* refers to systems of communication. These systems include human communication through spoken and written languages, non-verbal communication through gestures and facial expression, sounds produced by mammals and birds, and artificial computing languages [Simpson and Weiner, 2009]. Common to all languages is an *alphabet* Σ of basic elements, such as the letters of the Latin alphabet. When these elements are concatenated according to specific rules, they can form meaningful units, such as words and sentences. The structure of a language can be formally defined in a syntactic notation (see Appendix E).

Characteristics of tactile languages

Every tactile communication system, in fact, also establishes a language. Tactile languages can differ in the elements of their alphabet, the artificial tactile signals that represent these elements, the size of the alphabet, the intended application domain, and the body areas where the tactile signals stimulate the skin. We have primarily classified existing tactile languages based on their basic elements, which can be characters or words.

7.1.1 Characters as Basic Elements

Textual information transfer

One class of tactile languages uses alphabets that consist of characters and numerals as basic building blocks for composing messages. These languages typically aim at textual information transfer. For this reason, the size of their alphabets tends to be large. The most notable system to demonstrate that tactile communication is effective and that tactile stimuli can substitute spoken languages is the Braille alphabet. Braille can be read by moving the fingertips over a pattern of raised and lowered dots, which can represent characters, numerals, and punctuation (see Fig. 5.4, left). Another system that can be applied over the tactile channel is the Morse code [Geldard, 1957], although this code was originally developed for the

electric telegraph to transmit letters and numerals as short and long pulses of electrical current.

Inspired by the idea that the skin could understand a language based on vibrotactile stimuli that vary in amplitude, duration, and location [Geldard, 1957], two systems have been invented for encoding written text as tactile messages (see section 5.4.1). The Vibratese language encoded an alphabet of 45 symbols—letters and numerals—as variations in three intensities, three durations, and five locations at the chest [Geldard, 1957]. A trained user could perceive 38 words per minute, twice as much as with Morse code. The Optohapt system used actuators distributed at the arms, the legs, and the abdomen for conveying characters as tactile signals [Geldard, 1966]. Although these tactile languages are not established in use, they demonstrated that sequential and coded data could be processed quickly and accurately over the tactile sense.

Vibrotactile languages for text messages

Besides the aforementioned tactile languages, there are alternative methods for supporting speech communication. For example, *Tadoma* is a method where deaf-blind people place their fingers on the face of the speaker to pick up movements and vibrations of utterances conveyed through the lips, cheeks, jaw, and throat [Reed et al., 1985]. Also, Tactaid devices that converted sound into vibration patterns could support hearing-impaired people [Weisenberger and Percy, 1994] (see section 5.4.1). These methods for communication could be regarded to establish tactile languages as well because the tactile stimuli that are perceived and interpreted serve as an alphabet of elements that can form meaningful units.

Visually and hearing impaired persons communicate by touch

7.1.2 Words as Basic Elements

A different class of tactile languages uses alphabets with elements that represent a high-level concept from the intended application domain. These elements are expressed as words in spoken languages. In contrast to the aforementioned languages for textual information transfer, they do not require high data throughput because they do not convey individual characters as tactile signals for composing messages. For this reason, these alphabets usually comprise only a few elements. If the generated tactile signals rely on the accurate perception of the tactile parameters used for encoding information, data transfer typically takes place over the fingertips.

Tactile stimuli that represent application domain concepts

Some of these languages aim at information transfer in computer interfaces. For example, Tactons (see section 5.3) could represent events in GUIs: while one-element Tactons could denote commands and objects, such as “create”, “destroy”, “file”, or “string”, compound Tactons could communicate messages like “create file” or “destroy string” [Brewster and Brown, 2004]. Likewise, haptic icons [Enriquez et al., 2006] (see section 5.3) could convey information on the state, function, or content of events or objects with which people interact. These haptic icons are based on an alphabet of nine well differentiable stimuli, called haptic phonemes, which are concatenated

Tactile languages for information transfer in computer interfaces.

and superimposed to form haptic words. Also, a language for conveying emotional information such as affection and pain has been investigated [Benali-Khoudja et al., 2005] (see section 5.4.5). This language is based on an alphabet of six elements, which were applied to the fingertips and encoded as tactile stimuli that users associated with specific emotions.

Tactile languages for navigation signals and for hand signals

Besides the aforementioned languages for computer interfaces, two other languages have been explored. One language was based on an alphabet of eight words and focused on conveying directional information for navigation, such as move forward, turn around, turn left, turn right, and stop [Jones et al., 2006] (see section 5.4.2). The other language had an alphabet of seven words and addressed military hand and arm signals [Jones et al., 2007]. Both interfaces stimulated the lower back for conveying these commands.

7.1.3 A Tactile Language for Physical Activities

Tactile stimuli that represent body movements as basic elements

The tactile language introduced in this work uses words and sentences from the intended application domain as basic elements of the alphabet. These elements—tactile motion instructions—represent specific body movements (see Table 6.4 for the acronyms).

$$\Sigma = \{SL, FL, WL, WR, LL, LR, LF, LB, TL, TR\}$$

The underlying tactile signals that represent these elements are delivered to body locations that correspond to the chosen body movements.

Compound instructions communicate sequences of body movements.

Compound instructions are combinations of these basic elements. These combinations could communicate sequences of body movements. For example, the sequence $FL \rightarrow SL$ would prompt to flex the legs and subsequently to stretch the legs (see section 6.1.4 for the notation). Overall, the basic elements of the alphabet and the combinations of these elements establish a tactile language for physical activities.

7.2 Compound Tactile Motion Instructions

Single and compound instructions that based on the push and pull metaphor

The findings of our previous studies revealed that young adults were able to quickly learn a set of ten tactile motion instructions and to identify these instructions with high accuracy in active situations (see chapter 6). In this section, we will report a study that focused on two issues regarding these instructions. First, we explored if young adults could perceive and identify compound instructions. In contrast to single instructions, compound instructions required users to respond to a sequence of messages. Second, we investigated if the encoding metaphor for these instructions, based on stimuli that could be described to push or to pull the body, influenced the ability to respond to single and compound instructions.

To evaluate an example tactile language for physical activities, we used the Nintendo Wii Fit balance board and the game Slalom Snowboard for simulating an active situation in the laboratory (see also section 6.3.1). Since playing this game resembled real snowboarding, we defined compound instructions that were based on body movements that would also occur in snowboarding, including movements that were required for basic turns (see section 4.2). Overall, we have chosen compounds that would not hinder the participants in moving their bodies while balancing on the board.

We evaluated an example language in an active situation on the Wii fit balance board.

This example language L comprised 22 words: the ten basic instructions from the alphabet Σ (see Table 6.4 for the acronyms)

- $SL, FL, WL, WR, LL, LR, LF, LB, TL, TR,$

and twelve compound instructions. Four compounds addressed movements of the lower body and the upper body (shift the weight to one foot, then turn left or right)

- $WL \rightarrow TL, WL \rightarrow TR, WR \rightarrow TL, WR \rightarrow TR,$

four compounds exclusively addressed upper body movements (lean sideways, then turn the upper body)

- $LL \rightarrow TL, LL \rightarrow TR, LR \rightarrow TL, LR \rightarrow TR,$

and four compounds exclusively addressed lower body movements (shift the weight to one foot, then flex or stretch the legs)

- $WL \rightarrow FL, WL \rightarrow SL, WR \rightarrow FL, WR \rightarrow SL.$

Regarding the encoding metaphor for tactile motion instructions, our initial findings on the intuitive interpretation of tactile stimuli revealed that our participants preferred to move either towards or away from the vibration (see section 6.2). Even so, we did not consider the participants' preference to being pushed or pulled in the previous experiments. The mapping between the stimuli and their meaning was based on the push metaphor to keep all instructions consistent for all participants. In active situations, however, some instructions were misinterpreted. We surmised that the push metaphor might have caused these misinterpretations, besides left-right confusion when responding verbally and randomly applied instructions that could have interfered with the movements that the participants already had to perform during the activity. In fact, some participants stated that they expected the pull metaphor for instructions. Moreover,

Two metaphors for encoding the meaning of tactile instructions: push vs. pull

some participants stated that they did not like to execute movements at inappropriate times while descending the slope (see sections 6.3.1 and 6.3.2).

To independent variables: the situation and the mapping for instructions

To narrow down the possible reasons that could have caused misinterpretations in the active situation, we investigated if the encoding metaphor influenced the ability to recognize tactile motion instructions, depending on whether the instructions represented the participants' intuitive reactions (pull or push) or counter-intuitive reactions (push instead of pull or pull instead of push). Overall, we had two independent variables: the situation (stationary vs. active) and the mapping between the instructions and their meaning with respect to the participants' preference to the push and pull encoding metaphor (intuitive vs. counter-intuitive instructions).

We expected that counter-intuitive instructions would cause more misinterpretations than intuitive instructions in the active situation but not in the stationary situation.

As in our previous studies, the participants were asked to utter the meaning of the perceived messages before executing the instructions because the experimenter could not always accurately differentiate between body movements that were performed as response to tactile instructions and body movements that were required in the current gameplay situation. For the stationary situation, we expected that neither encoding metaphor would cause many misinterpretations because the participants would not be distracted when responding verbally. For the active situation, we expected that the participants would misinterpret instructions, as was also the case in our previous experiments. We surmised, however, that instructions that represented the participants' counter-intuitive reactions would increase the number of misinterpretations compared to instructions that represented their intuitive reactions. We argued that the participants' intuitive reactions could interfere with the new mappings that they would learn for counter-intuitive instructions. If this were the case, the encoding metaphor would influence their responses with counter-intuitive instructions causing more misinterpretations than intuitive instructions in the active situation.

The first hypothesis was:

- Alternative hypothesis: In the stationary situation, users who receive instructions based on their counter-intuitive metaphor (push instead of pull or pull instead of push) do not perform more mistakes than users who receive instructions based on their intuitive metaphor.
- Null hypothesis: In the stationary situation, counter-intuitive instructions cause more mistakes than intuitive instructions.

The second hypothesis was:

- Alternative hypothesis: In the active situation, users who receive instructions based on their counter-intuitive metaphor (push instead of pull or pull instead of push) perform more mistakes than users who receive instructions based on their intuitive metaphor.
- Null hypothesis: In the active situation, counter-intuitive instructions do not cause more mistakes than intuitive instructions.

7.2.1 Participants and Experimental Setup

Twenty volunteers aged 22–29 years ($M = 24.60$ years, four women) were recruited from the local university. All volunteers stated to regularly practice sport. Two participants snowboarded. One participant skied. Two participants had previously played with the balance board but not with the snowboarding game. None of the volunteers had previously experienced artificial tactile stimuli in relation to tactile motion instructions.

The participants wore the custom tactile suit with 30 vibration motors. Five SensAct boxes (see Fig. 3.5) were stored in a backpack such that all words from the language L could be applied: the ten basic instructions; and the twelve compound instructions.

All instructions were applied.

To familiarize the candidates with the sensations that the tactile patterns evoked on the skin, the experimenter triggered the basic instructions from the alphabet once. Then, the participants' preference to moving towards (pull) or away (push) from the vibration was determined. Based on forced-choice paradigm, the participants stated in which direction they preferred to move upon perceiving the stimuli at the chest, at the back, laterally at the torso, and laterally at the thighs.

Determining the preferred encoding metaphor

A between-subjects design was chosen for assessing if the encoding metaphor would influence the ability to learn and to recognize the tactile instructions. The participants were divided into two groups: an intuitive group and a counter-intuitive group. Every second volunteer was assigned to the counter-intuitive group where the mapping between the tactile patterns and their meaning was counter-intuitive: participants who preferred the pull metaphor received instructions based on the push metaphor; participants who preferred the push metaphor received instructions based on the pull metaphor. In contrast, the members of the intuitive group received instructions based on their preferred encoding metaphor.

Intuitive vs. counter-intuitive instructions

Fig. 7.1 illustrates the tactile patterns that prompted to move towards the vibration (pull metaphor), which we have previously illustrated in Fig. 6.18. Note that directional lines in upward direction at the front of the thighs were described to pull flexed legs upward (stretch legs), whereas directional lines in downward direction at the back of the thighs were described to pull stretched legs downward (flex legs). The directional line around the left shoulder ran from the chest to the back and signaled to turn left, whereas the directional line around the right shoulder ran from the chest to the back and signaled to turn right.

Instructions based on the pull metaphor

Fig. 7.2 illustrates the tactile patterns that prompted to move away from the vibration (push metaphor). Note that directional lines in downward direction at the front of the thighs were described to push stretched legs downward (flex legs), whereas directional lines in upward direction at the back of the thighs were described to push flexed legs upward (stretch legs). The directional line around the left shoulder ran from the back to the chest

Instructions based on the push metaphor

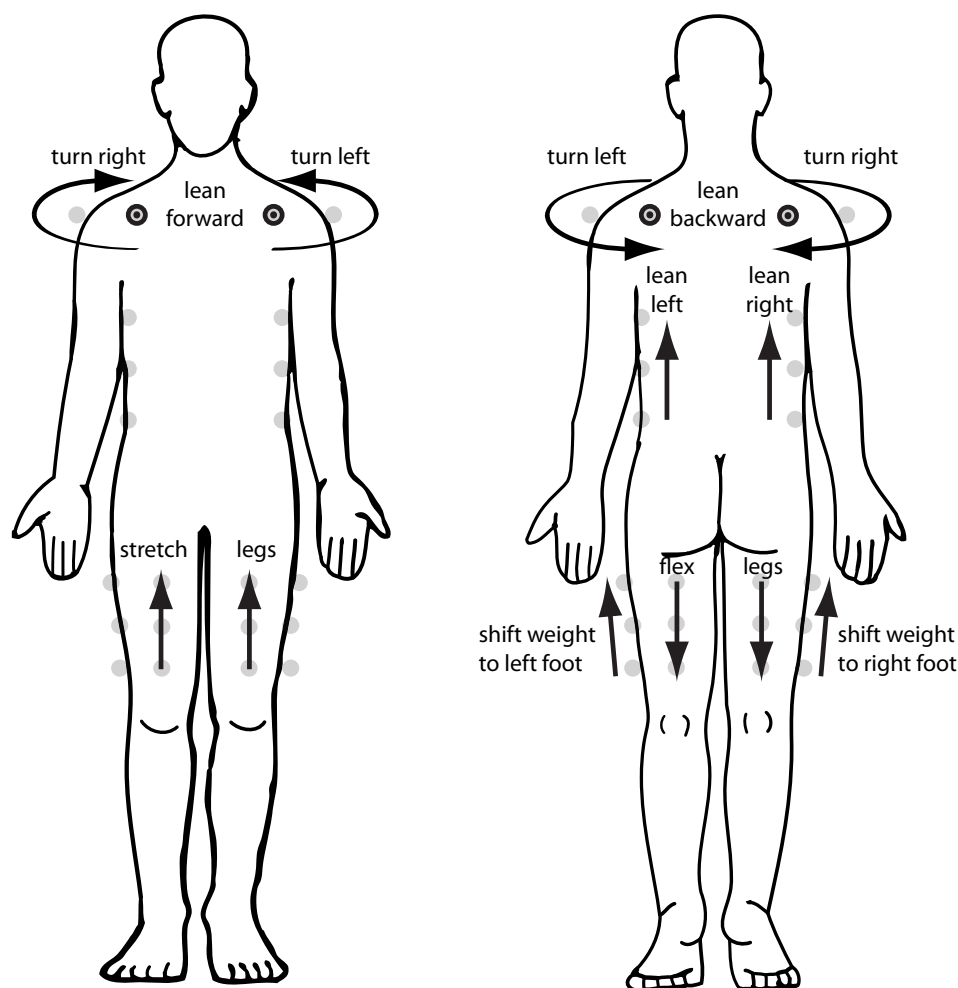


Figure 7.1: Tactile motion instructions based on the pull metaphor stimulated the same site of the body in which to perform movements.

and signaled to turn right, whereas the directional line around the right shoulder ran from the back to the chest and signaled to turn left.

Training session
for learning the
alphabet of the
language

In order to learn their customized instruction sets—the alphabet of our example language—the participants stood upright in front of a 40-inch display and pressed buttons on the GUI of the SensAct Control application, which triggered the corresponding tactile patterns for the ten basic instructions (see Fig. 3.9). They were allowed to practice as long as they wished, but the total training time was limited to ten minutes. After learning the meaning of the patterns, they played the game for two to three times in order to become familiar with controlling the snowboard on the screen while balancing on the board.

Single and
compound
instructions were
tested

The experiment started after this training session. The participants were informed that they would receive single instructions from the previously learned set, which were the ten basic elements of the alphabet. Besides these (basic) single instructions, they would also receive compound instructions that consisted of two sequentially triggered basic instructions. Since

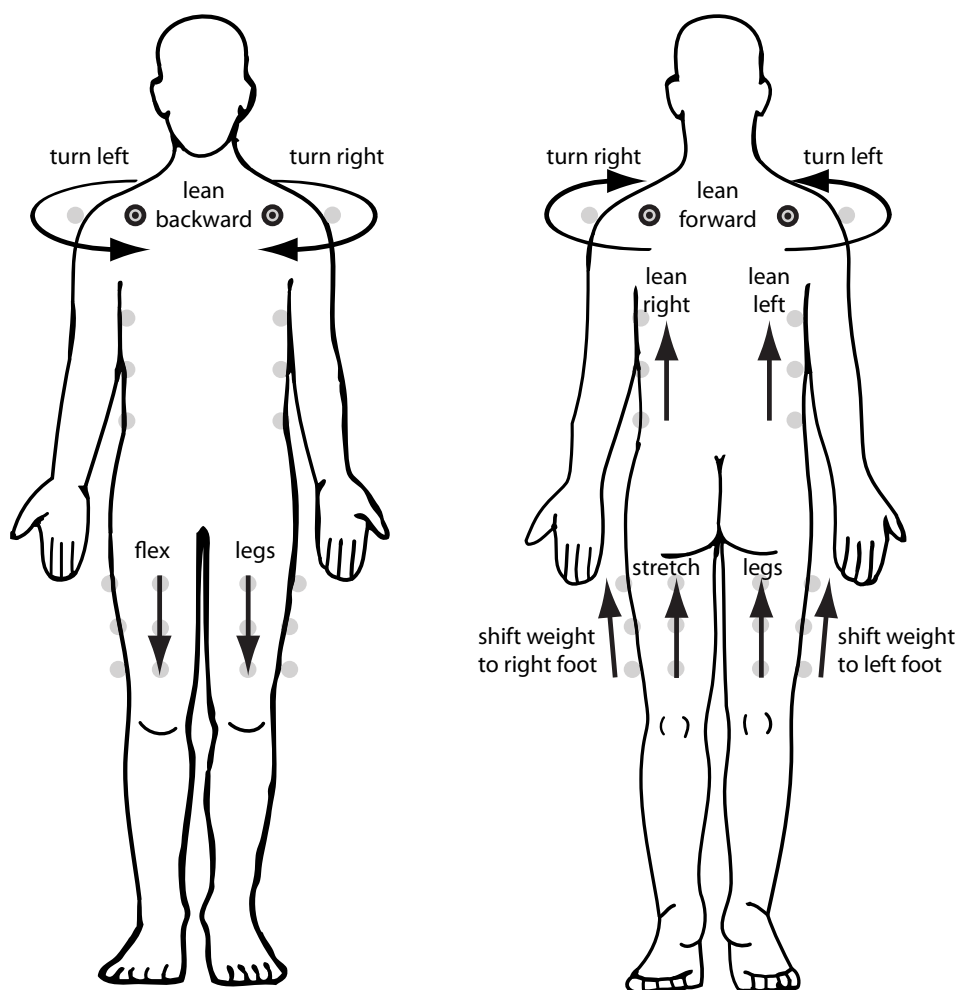


Figure 7.2: Tactile motion instructions based on the push metaphor stimulated the opposite site of the body in which to perform movements.

the participants did not learn compound instructions during the training session, they did not know which combinations of basic instructions to expect. This allowed us to estimate how well they could make use of the tactile language in the static and in the active situation.

The participants' task was to say out aloud the meaning of these messages before performing the corresponding movements. The stationary situation served as baseline for the optimal perception and interpretation of all 22 tactile motion instructions from the language *L*. The participants stood still and listened to soft music played back over headphones, which blocked the auditory cues from the vibrating motors. In the active situation, they heard the sound of the game played back over loudspeakers while passing between the flags on the screen as accurately as possible.

Two situations for responding to instructions

The order of the stationary and active situation was counterbalanced across the participants. The experimenter randomly triggered all basic and compound instructions twice in each situation. After recording a participant's response, a random delay between 10–15 seconds was chosen before an-

Counterbalanced situations

Table 7.1: Number of participants who preferred to be pulled or pushed.

| Stimulus location | Pull | Push |
|----------------------------|------|------|
| Upper chest | 13 | 7 |
| Upper back | 11 | 9 |
| Lateral side of the torso | 11 | 9 |
| Lateral side of the thighs | 11 | 9 |

other word from the language was triggered. In the active situation, the participants replayed the game until all instructions were applied.

7.2.2 Results

Preference to the push or the pull metaphor

Table 7.1 shows the participants' preference to moving towards or away from stimuli. Nine participants intuitively preferred the pull metaphor for all stimuli that were delivered to the chest, to the back, and laterally to the torso and the thighs. Seven participants preferred the push metaphor for these stimuli, yet two of them moved towards pulses delivered to the chest.

Mixed push and pull metaphor

Four participants preferred a mixed metaphor: one moved towards stimuli delivered to the chest and back but away from lateral stimuli delivered to the torso and the thighs; one moved away from stimuli delivered to the chest and back but towards lateral stimuli delivered to the torso and the thighs. The other two participants preferred the same metaphor for stimuli delivered to the chest, to the back, and laterally to the torso, but they responded differently to stimuli delivered laterally to the thighs: one moved away, and one moved towards these stimuli. The preferred encoding metaphor for these participants—push or pull—was chosen based on their most frequent reactions to avoid mixed mappings in the instruction set.

Seven participants did not respond to a few compound instructions.

In the active situation, three participants were absorbed in playing the game and often answered only on request from the experimenter. To avoid speaking, some participants expressed the meaning of the instructions with gestures of their hands and arms. Nine compound instructions were missed: four members of the intuitive group each missed one compound instruction; two members of the counter-intuitive group each missed one compound instruction, whereas one member missed three. Two members of the counter-intuitive group correctly recognized all instructions in both situations.

Overall, both groups recognized instructions with similar accuracy.

Table 7.2 summarizes the average percentage of recognized instructions. A mixed between-within ANOVA revealed no significant main effect of the group, $F(1, 18) = .035, p = .85, r = .04$, indicating that the ability to recognize intuitive and counter-intuitive instructions was in general the same if we ignore the other factors.

The active situation degraded the performance; basic instructions were best recognized.

There was a significant main effect of the situation, $F(1, 18) = 7.14, p = .016, r = .53$, indicating that the ability to recognize instructions degraded in the active situation compared to the stationary situation. There was

Table 7.2: Average accuracy in responding to the ten basic instructions and to the twelve compound instructions encoded based on the participants' intuitive or counter-intuitive metaphor (in %, with standard deviation).

| Situation | Instruction type | Intuitive group | Counter-intuitive group | Both groups |
|------------|------------------|---------------------|-------------------------|---------------|
| Stationary | all | 99.77 (0.72) | 95.23 (7.38) | 97.50 (5.61) |
| | basic | 99.50 (1.58) | 96.00 (5.68) | 97.75 (4.44) |
| | compound | 100.0 (0.00) | 94.58 (10.40) | 97.29 (7.68) |
| Active | all | 90.00 (6.96) | 94.32 (4.94) | 92.16 (6.28) |
| | basic | 97.50 (3.54) | 96.50 (4.12) | 97.00 (3.77) |
| | compound | 83.75 (10.84) | 92.50 (7.81) | 88.13 (10.23) |
| Both | all | 94.89 (6.95) | 94.77 (6.13) | 94.83 (6.47) |
| | basic | 98.50 (2.86) | 96.25 (4.83) | 97.38 (4.08) |
| | compound | 91.88 (11.19) | 93.54 (9.01) | 92.71 (10.06) |

a highly significant main effect of the type of instructions, indicating that basic instructions were more often recognized than compound instructions, $F(1, 18) = 14.66, p < .01, r = 0.67$.

There was a significant interaction effect between the situation and the group, $F(1, 18) = 5.04, p = .038, r = 0.47$. This indicates that the ability to respond to instructions in the stationary and active situation differed between the intuitive and counter-intuitive group if we ignore the type of instructions. The intuitive group performed better than the counter-intuitive group in the stationary situation, but the counter-intuitive group performed better than the intuitive group in the active situation. Although the counter-intuitive group performed similarly in both situations, the intuitive group performed worse in the active than in the stationary situation.

There was no significant interaction effect between the type of instructions (basic vs. compound) and the group, $F(1, 18) = 2.58, p = .13, r = 0.35$. This suggests that the ability to identify basic and compound instructions was in general the same for the intuitive and counter-intuitive group if we ignore the situation.

There was a highly significant interaction effect between the situation and the type of instructions, $F(1, 18) = 12.44, p < .01, r = 0.64$. This indicates that the ability to respond to basic and compound instructions differed in the stationary and active situation if we ignore the group. Basic instructions were recognized with similar accuracy in both situations, but compound instructions were more accurately recognized in the stationary than in the active situation. Although the ability to recognize instructions decreased in the active situation compared to the stationary situation, this decrease mainly affected compound instructions but not basic instructions.

The situation \times instruction type \times group interaction effect was significant, $F(1, 18) = 5.98, p = .025, r = 0.50$. This indicates that the situation \times instruction type interaction was different for the groups. In the stationary

The intuitive group performed better than the counter-intuitive group in the stationary situation but worse in the active situation.

Both groups recognized basic and compound instructions with similar accuracy.

Basic instructions were recognized well in both situations; compounds were best recognized while stationary.

The intuitive group often misinterpreted compound instructions in the active situation.

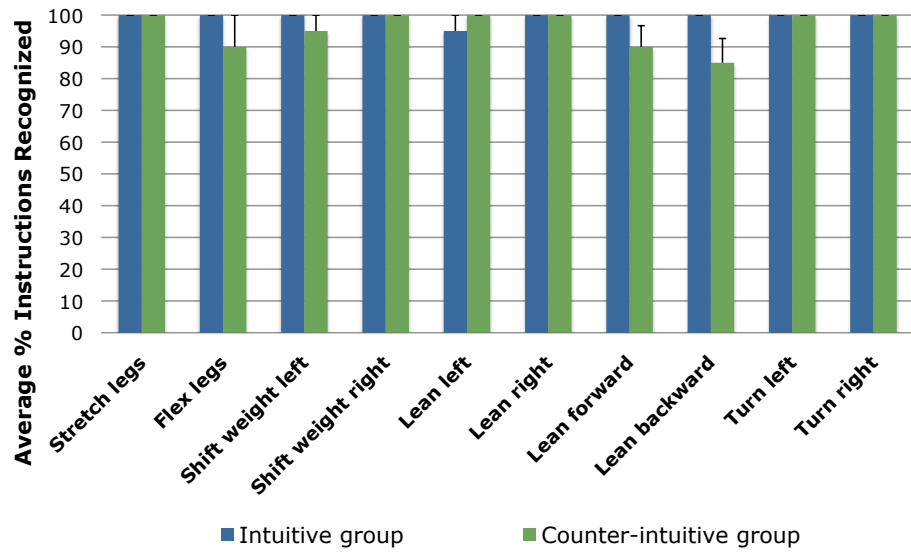


Figure 7.3: Average percentage of recognized basic instructions in the stationary situation (with standard error).

Table 7.3: Number of participants who misinterpreted basic instructions in the same category (see Table 6.4 for categories). The row “distinct users” denotes the number of different participants across both situations.

| | Situation | C1 | C2 | C3 | C4 | C5 |
|-------------------------|----------------|----|----|----|----|----|
| Intuitive group | stationary | | | 1 | | |
| | active | 1 | 2 | 1 | 1 | |
| | distinct users | 2 | | | | |
| Counter-intuitive group | stationary | 1 | 1 | | 4 | |
| | active | 2 | 2 | 1 | 1 | |
| | distinct users | 2 | 2 | 5 | | |

situation, the intuitive group recognized basic and compound instructions with near-perfect accuracy, and the performance of the counter-intuitive group was slightly worse than the performance of the intuitive group. In the active situation, the ability to recognize basic instructions was similar for both groups, although the performance of the intuitive group slightly decreased, whereas the performance of the counter-intuitive group basically did not change compared to the stationary situation. The main difference between the groups concerned compound instructions. Although the ability to recognize these instructions decreased for both groups in the active situation compared to the stationary situation, this decrease was more pronounced for the intuitive group than for the counter-intuitive group.

Recognition of
basic instructions

Fig. 7.3 illustrates which basic instructions were recognized in the stationary situation. The counter-intuitive group ($M = 96.0\%$, $SE = 1.80\%$) performed worse than the intuitive group ($M = 99.5\%$, $SE = .5\%$); the difference between the profiles of the recognized instructions was significant $t(10.39) = 1.88$, $p = .045$, $r = .40$ (independent t-test, one-tailed,

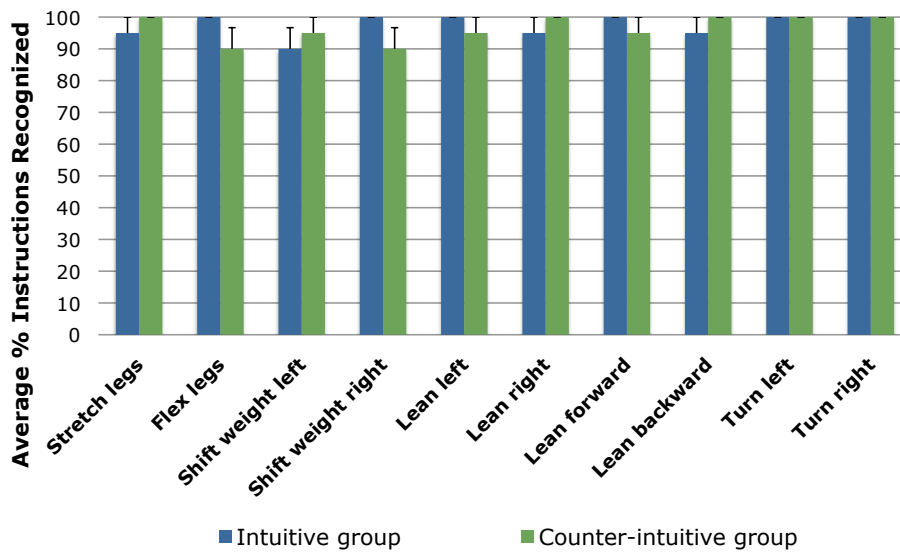


Figure 7.4: Average performance of recognized basic instructions in the active situation on the Wii balance board (with standard error).

Table 7.4: Number of misinterpreted patterns for compound instructions (see Table 6.4 for categories). The last two columns show the number of mistakes for the first and second pattern of compound instructions.

| | | C1 | C2 | C3 | C5 | 1st | 2nd |
|-------------------------|------------|----|----|----|----|-----|-----|
| Intuitive group | stationary | | | | | | |
| | active | 2 | 27 | 6 | 7 | 33 | 9 |
| Counter-intuitive group | stationary | 7 | 3 | 1 | | 4 | 7 |
| | active | 4 | 8 | | 6 | 8 | 10 |

equal variances not assumed). Fig. 7.4 illustrates which basic instructions were recognized in the active situation. The counter-intuitive performed similarly ($M = 96.5\%$, $SE = 1.30\%$) to the intuitive group ($M = 97.5\%$, $SE = 1.12\%$); the difference between the profiles was not significant $t(18) = .58$, $p = .28$, $r = .14$ (independent t-test, one-tailed, equal variances assumed).

Table 7.3 summarizes the number of participants who misinterpreted basic instructions. Although only few participants had difficulties with basic instructions, half of the members of the counter-intuitive group occasionally misinterpreted the instructions in category C4 (*Lean forward* and *Lean backward*). Four of these participants responded incorrectly in the stationary situation but not in the active situation.

Fig. 7.5 shows which compound instructions were recognized in the stationary situation. The counter-intuitive group performed worse ($M = 94.58\%$, $SE = 1.56\%$) than the intuitive group ($M = 100\%$, $SE = 0\%$); the difference between the profiles of the recognized instructions was highly significant $t(11) = 3.46$, $p < .01$, $r = .59$ (independent t-test, one-tailed,

The counter-intuitive group misinterpreted basic instructions in the stationary situation.

Recognition of compound instructions

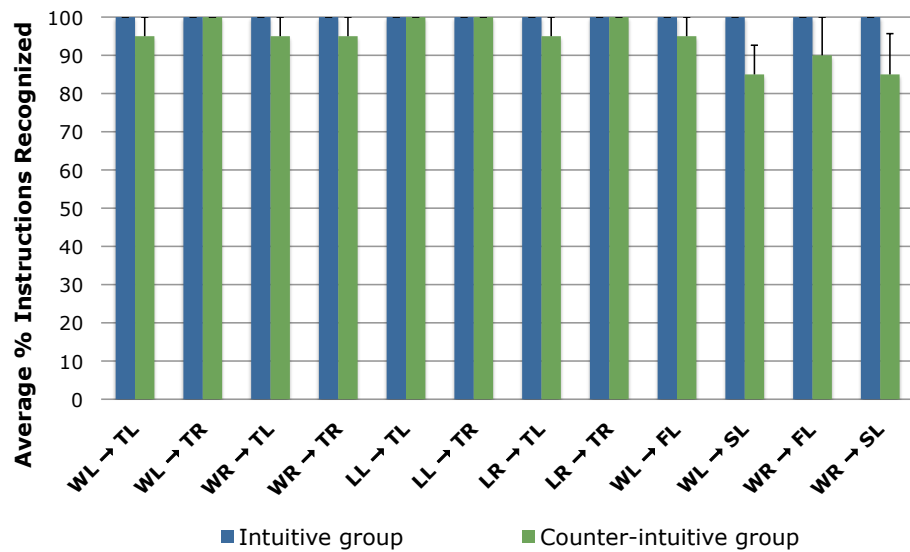


Figure 7.5: Average percentage of recognized compound instructions in the stationary situation (with standard error).

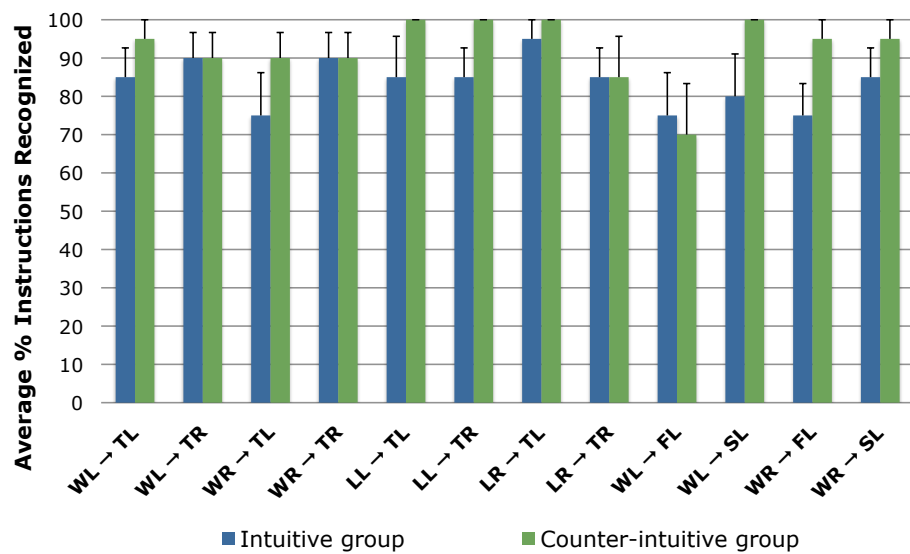


Figure 7.6: Average percentage of recognized compound instructions in the active situation on the Wii balance board (with standard error).

equal variances not assumed). Fig. 7.6 shows which compound instructions were recognized in the active situation. In contrast to the stationary situation, the intuitive group performed worse ($M = 83.75\%$, $SE = 1.86\%$) than the counter-intuitive group ($M = 92.50\%$, $SE = 2.50\%$); the difference between the profiles was highly significant $t(22) = -2.81$, $p < .01$, $r = .51$ (independent t-test, one-tailed, equal variances assumed). Overall, the counter-intuitive group performed similarly in both situations, whereas the intuitive group identified all compound instructions in the stationary situation but often misinterpreted them in the active situation.

Table 7.4 summarizes the number of misinterpreted compound instructions. The intuitive group most often misinterpreted the first element of these instructions, which was an instruction from the category *C2 (Shift weight left (right))* in eight of the twelve compounds. Overall, two participants had difficulty with these instructions and performed 41.03% of all mistakes. Also, the four volunteers who preferred a mixed metaphor were randomly assigned to this group and performed 33.33% of all mistakes. Even so, this group correctly recognized all compound instructions in the stationary situation. In contrast, the counter-intuitive group misinterpreted compound instructions in both situation, but this group had less difficulty with the first element of these instructions than the intuitive group.

Two members of the intuitive group most often misinterpreted compound instructions.

Both groups recognized the instructions *Turn left (right)* as single instructions in the stationary situation and in the active situation. Even so, both groups misinterpreted these instructions a few times in the active situation when these instructions were applied as the second element of a compound.

Upper body turns were misinterpreted in compound instructions.

The participants did not mention to have problems in learning the set of basic instructions. Even so, some participants stated that they could benefit from a longer training session, although they practiced less than the allotted time. The tactile patterns around the shoulders, which represented *Turn left (right)*, were clear to follow. One former ballet dancer considered tactile instructions appropriate for dance training; they reminded her of dance lessons, rotation around the shoulders in particular. Another participant stated that he liked tactile instructions. He had more fun playing the game with these instructions than practicing on the Wii balance board without tactile feedback. Also, he mentioned that these instructions could indicate which movements to perform in order to guide the user during exercises.

Learning the instructions was not problematic.

Apart from these positive comments, two participants commented that the instructions did not always match to the movements that they had performed while playing the game, which made it difficult to accurately pass through the flags and to move the body as instructed. Also, a few participants stated that they tended to mix up the directions while speaking, although they knew what the patterns actually meant.

The participants disliked random instructions and verbal responses.

Two participants who learned instructions based on the push metaphor commented on the nature of the stimuli that were applied to the back of their thighs, which moved upwards to represent *Stretch the legs*. Since these stimuli were close to the hollow of the knees, they would resemble a slight stroke that would automatically trigger knee flexion. Therefore, they considered these patterns more appropriate for indicating *Flex the legs*.

Stimuli at the back of the thighs should indicate knee flexion.

7.2.3 Discussion

In this study, we have investigated if compound tactile motion instructions could communicate body motion sequences in a similar way as sentences can convey instructions in spoken languages. Considering the participants'

A tactile language for physical activities.

intuitive and counter-intuitive reactions to the chosen tactile patterns, we have assessed how accurately the participants could recognize basic and compound instructions in a stationary situation and in an active situation on the Wii balance board. Overall, our findings indicate that tactile motion instructions form a simple language and that this language can communicate sequences of instructions that could describe how to move the body in physical activities.

Both encoding metaphors can be applied for encoding in which direction to move.

Considering our participants' overall performance in responding to tactile instructions in the active situation on the balance board, we can summarize three main findings. First, both intuitive and counter-intuitive instructions were recognized with high accuracy. Overall, less than 6% of these instructions were misinterpreted. This finding indicates that the encoding metaphor did not influence the ability to verbally respond to tactile instructions. Those participants who preferred to be pushed and those who preferred to be pulled could learn and identify instructions with reversed mapping. This suggests that both encoding metaphors can be applied regardless of the user's preference to moving away or towards the vibration.

Compound instructions were longer and required more attention to utter their meaning.

Second, basic (single) instructions were more accurately recognized than compound instructions. One reason that could have diminished the ability to identify compound instructions is that compounds were longer than single instructions. In our case, these compounds required more attention to remember and to utter their meaning than single instructions. Had our participants only performed the movements without uttering the meaning of the instructions, we surmise that their ability to identify compound instructions would have been similar to their ability to identify single instructions. Another reason could be that our participants did not know which compound instructions to expect. Had they also learned the set of compound instructions when they learned the set of basic instructions, they might have better recalled the meaning of these instructions.

The active situation degraded the ability to identify instructions.

Third, the active situation degraded the ability to name the instructions compared to the stationary situation. This finding corresponded to the findings of our previous studies (see section 6.3). Even so, considering the situation and whether single or compound instructions were applied, the intuitive and counter-intuitive group performed differently.

Counter-intuitive basic and compound instructions were misinterpreted in the stationary situation.

In the stationary situation, regarding basic and compound instructions, the participants who received these instructions based on their preferred encoding metaphor performed on average fewer mistakes than the participants who received these instructions based on their counter-intuitive metaphor. Moreover, the profiles of the recognized instructions significantly differed between the groups. We did not expect that the groups would perform differently in the stationary situation because our participants were not distracted when they responded verbally. For this reason, we have failed to reject the first null hypothesis, which stated that counter-intuitive instructions cause more mistakes than intuitive instructions. According to this finding, intuitive instructions should be applied in stationary situations.

The results were different in the active situation. Both groups recognized basic instructions with similar accuracy. Also, the profiles of these instructions did not significantly differ between the groups. Even so, the intuitive group misinterpreted more than twice as many compound instructions (16.25%) than the counter-intuitive group (7.50%). This finding was surprising because on average both groups recognized basic instructions with similar accuracy in both situations. For this reason, we have failed to reject the second null hypothesis, which stated that counter-intuitive instructions do not cause more mistakes than intuitive instructions. According to this finding, counter-intuitive instructions should be applied in active situations.

Intuitive compound instructions were misinterpreted in the active situation.

These findings are contradicting. The post-study analysis, however, revealed that the intuitive and counter-intuitive groups were not equally balanced regarding the participants' preference for the encoding metaphor and their ability to respond verbally to compound instructions while balancing on the board. Four participants preferred a mixed metaphor. They were randomly assigned to the intuitive group and had to learn and to respond to two counter-intuitive instructions. Also, the intuitive group included two participants who performed poorly for compound instructions but not for basic instructions. Overall, mainly these six participants misinterpreted compound instructions in the active situation. Moreover, they had difficulty in naming the first element of compound instructions, which was further back in time. This indicates that uttering the meaning of compound instructions challenged these participants while playing the game. We assume that these were the main reasons why the intuitive group performed worse for compound instructions in the active situation than the counter-intuitive group, although the intuitive group recognized all compound instructions in the stationary situation. Had the groups been better matched and had the participants not responded verbally, we surmise that both groups might have recognized compound instructions with similar accuracy.

The groups were not equally balanced.

For both groups, the profiles of the recognized basic instructions were similar to the profiles measured with different participants in the first study on the balance board (see section 6.3.1). In this former study, all participants received instructions based on the push metaphor, although some of them might have preferred the pull metaphor. The main difference between the results of these studies is that in contrast to the directional lines around the waist, the semicircular lines around the shoulders have been correctly recognized. This indicates that the semicircular lines were appropriate as tactile patterns for representing *Turn left (right)*. Moreover, our participants could learn and recognize these counter-intuitive instructions.

The tactile patterns for upper body rotation were correctly recognized.

Overall, the findings of this study indicate that tactile motion instructions can establish a simple language. Also, young adults can perceive and recognize basic and compound instructions with high accuracy in an active situation, although they might misinterpret some instructions if they respond verbally. The experimental conditions, however, were the same as in our previous studies and should be considered when interpreting the aforementioned findings. Randomly applied instructions did not always match to the movements that were required while playing the game. A few par-

Random instructions and left/right confusion influenced the responses.

participants mentioned to have mixed up directions when responding verbally, which increased the cognitive workload on them. Also, our user groups comprised ten participants; the results might vary for larger groups. For these reasons, we surmise that the ability to recognize tactile motion instructions was better than we could measure with the technology that we had available. Further studies are required to confirm our assumption once body movements can be automatically classified without requiring the participants to respond verbally, and by applying only instructions that do not interfere with movements that have to be performed during the activity.

7.3 Characteristics of Tactile Motion Instructions

Intuitive interpretation of tactile stimuli

We have started our investigation into tactile motion instructions by observing how young adults intuitively interpreted artificial tactile stimuli (see section 6.2). These stimuli included localized pulses and directional lines that were applied to the chest, the back, the shoulders, and the lateral side of the torso and the thighs. Since our participants did not have previous experience with artificial tactile stimuli, their answers were unbiased. Also, they could assign any meaning to the experienced sensations without referring to a predetermined set of answers that could have influenced or restricted their responses.

The same stimulus can represent different movements.

We have found that the reactions to the stimuli often corresponded but also differed across the participants. For example, some participants preferred to move towards points of stimulation, while others preferred to move away; lateral pulses at the torso prompted to move the arm away from the body but also to lean sideways; lateral pulses at the thigh prompted to move the leg but also to redistribute the weight from one foot to the other foot. Moreover, a stimulus that a participant could associate with a specific movement was sometimes too vague to carry meaning for another participant.

Tactile motion instructions are not universally intuitive.

Based on these findings, we have chosen those tactile stimuli as tactile motion instruction patterns that our participants most often associated with the same or with a similar body movement. Even so, the fact that these stimuli could be associated with more than one body movement implies that the mapping between a pattern and its meaning was intuitive for some participants but ambiguous to others. Consequently, some participants had to learn the meaning that we had assigned to these patterns.

Tradeoff between intuitiveness and discriminability

Moreover, tactile motion instruction patterns have to balance intuitiveness and discriminability. We have modified and changed some of the originally chosen patterns in order to make them perceivable and discriminable in active situations because some participants could not pay attention to the characteristics of the stimuli. For example, the directional lines around the waist, which represented *Turn left* or *Turn right*, were replaced with semicircular lines around the shoulder. These patterns were unique and discriminable in an active situation (see section 7.2). Even so, in a static situation they were less preferred than the directional lines around both

shoulders (see section 6.4), which in fact had the same drawbacks as the directional lines around the waist because they shared all actuators.

We did not explore whether the volunteers who participated in our subsequent studies regarded the proposed set of tactile motion instructions patterns as evident or not, but informal feedback from several candidates supported both views. In general, our participants regarded the instructions as easy to learn and described the mappings as intuitive. Also, some participants commented that stimuli at the back of the thighs should represent knee flexion. These stimuli occurred close to the hollow of the knees and naturally prompted to flex the legs, as if it was a knee-jerk reaction—a hint that this pattern intuitively represented this body movement. Many comments, however, were biased because our participants had already learned the meaning that we had assigned to the patterns. Also, some participants mentioned that longer training sessions could help to learn the set of instructions (see section 7.2), which indicated that they regarded some mappings as unfamiliar.

Many participants rated the learned instructions as intuitive.

The study described in this section re-evaluated how intuitive potential users regarded the set of tactile motion instruction patterns. In particular, we have addressed the following questions:

- How intuitive is the mapping between the designed tactile patterns and the body movements that they represent?
- How long do end-users need to learn these mappings?
- Do end-users recall these mappings after extended time?

Our assumption was that those tactile patterns whose meanings would be difficult to learn and to remember would be less appropriate for representing body movements in an intuitive way. These patterns would have to be modified further. If, however, the patterns were easy to learn and remember, we could argue that the designed set of patterns and the assigned mappings would be justifiable as tactile motion instructions. Moreover, we could argue that the experimental setup mainly lead to mistakes. In particular, our participants had to respond verbally, and they had to identify instructions that did not always match to the movements that they already had to perform in the active situation.

7.3.1 Participants and Experimental Setup

Nine volunteers aged 19–27 years ($M = 22.78$ years, two women) were recruited from the local university to participate on two consecutive days. None of them had previously experienced artificial tactile stimuli in relation to our technology. Neither did they know about the concept of tactile motion instructions. Eight participants did sports, preferably bicycling, jogging, table tennis, and climbing.

No previous experience with artificial tactile stimuli

The participants wore the custom-tailored tactile suit with 30 vibration motors and a backpack with five SensAct boxes (see Fig. 3.5). Throughout the study, they wore headphones and listened to soft music that blocked the auditory cues produced by the vibrating motors. To familiarize the participants with the tactile sensations, the experimenter first triggered all ten patterns depicted in Fig. 7.1 once in random order.

Intuitive interpretation of tactile stimuli

Then, each pattern was randomly triggered again. The participants were asked to state with which body movement they would intuitively respond. An open response paradigm was used for answers such that they could assign any meaning to the experienced sensations.

Preference to the push or the pull metaphor

Our first study on the intuitive interpretation of vibrotactile stimuli revealed that some patterns yielded vague or no answers (see section 6.2). Therefore, in this study, the experimenter re-triggered those patterns that did not yield a concrete response and that could clearly represent a push or a pull of the body: pulses at the chest and at the back; and directional lines laterally at the torso and at the thighs. Based on forced-choice paradigm, the participants stated in which direction they preferred to move.

No time limit for learning the customized instruction sets.

These answers determined the preferred encoding metaphor for the instructions that the volunteers had to subsequently learn. To retain the mappings that corresponded to the participants' intuitive responses, the experimenter considered mixed metaphors for the patterns that were applied to the chest, to the back, and laterally to the torso and the thighs. To retain the sensations that were experienced at the beginning of the experiment, the pull metaphor was used for knee flexion and extension, and for upper body rotation: directional lines in downward direction at the back of the thighs represented *Flex the legs*, which initially received the most responses (see section 6.2) and which were recommended by former participants (see section 7.2); lines in upward direction at the front of the thighs represented *Stretch the legs*; semicircular lines around the left (right) shoulder from the chest to the back represented *Turn left (right)* (see Fig. 7.1). The participants learned their customized instruction sets by pressing buttons the GUI of the SensAct Control application, which triggered the corresponding tactile patterns (see Fig. 3.9). They practiced as long as they wished, until they were sure to have memorized all mappings.

Short-term study for recalling tactile motion instructions

After this training session, the ten instructions were randomly applied for four times to record how well the participants remembered the meaning of the tactile patterns. These responses served as baseline for the optimal recall of the instructions. To record their long-term recall, we asked the participants to return on the following day. We did not mention the purpose of this post-test to avoid practice at home. After this post-test, the participants were asked to rate the mapping between the patterns and their meaning. In particular, we were interested if they had difficulty in learning and remembering the ten instructions.

Long-term study for recalling tactile motion instructions

Three months later, the participants were invited by e-mail to participate in a final study on tactile motion instructions. As before, all instructions

Table 7.5: Number of participants who preferred to be pulled or pushed.

| Stimulus location | Pull | Push |
|----------------------------|------|------|
| Upper chest | 5 | 4 |
| Upper back | 5 | 4 |
| Lateral side of the torso | 2 | 7 |
| Lateral side of the thighs | 3 | 6 |

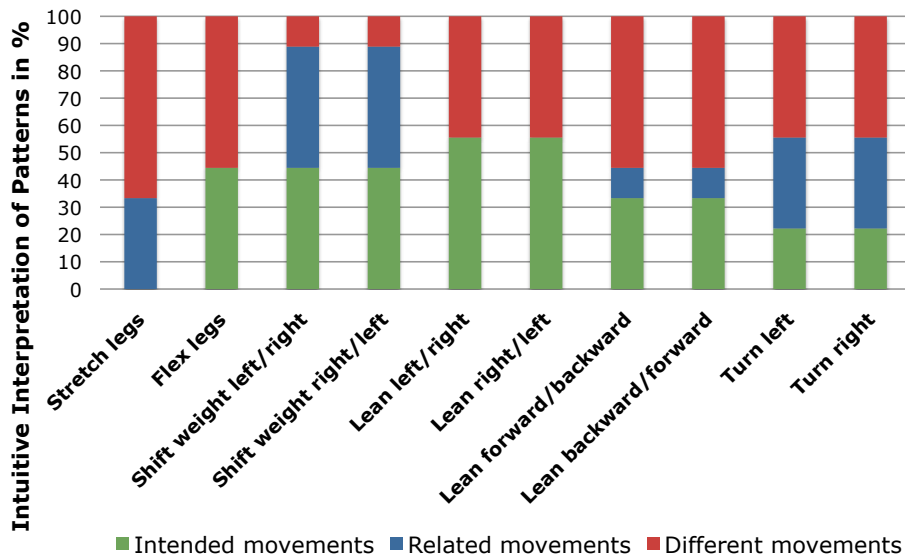


Figure 7.7: Intuitive interpretation of tactile patterns that could represent body movements. Abscissa labels denote the intended meaning of the patterns. We accepted both a push and a pull of the body as answers for stimuli that were applied to the back, to the chest, and laterally to the torso and the thighs.

were randomly applied for four times to record how well our candidates could recall the meaning of the tactile patterns.

7.3.2 Results

Table 7.5 shows the participants' preference to moving towards or away from stimuli. Three volunteers preferred the push metaphor, whereas one preferred the pull metaphor. The other five participants preferred a mixed metaphor: three moved towards pulses delivered to the chest and back but away from lateral stimuli to the torso and the thighs; one moved away from pulses delivered to the chest and back but towards lateral stimuli to the torso and the thighs; one moved away from pulses delivered laterally to the torso but moved towards the other stimuli.

We have classified the participants' intuitive responses into three categories. *Intended movements* comprised the answers that exactly represented the assigned meaning of the patterns ($M = 35.56\%$, $SD = 17.21\%$). *Re-*

Push, pull, and mixed metaphors

Three movement categories

Table 7.6: The participants’ intuitive answers to the tactile patterns (with frequency of the responses). For some instructions, we did not find answers that were related to the intended movements (none).

| Intended movements | Related movements | Different movements |
|------------------------|--|--|
| Stretch legs (0) | jump upwards (3) | bend legs (2), walk forward, hop forward, lift legs, walk backward |
| Flex legs (4) | (none) | walk forward (3), walk backward, stretch legs |
| Shift weight left (4) | lift left leg (4) (weight shifted to right foot) | don’t know |
| Shift weight right (4) | lift right leg (4) (weight shifted to left foot) | don’t know |
| Lean left (5) | (none) | turn left (2), lift arm, don’t know |
| Lean right (5) | (none) | turn right (2), lift arm, don’t know |
| Lean forward (3) | pushing sensation | don’t know (2), move shoulders forward, turn around, breath in |
| Lean backward (3) | straighten up | move shoulders backward (2), move forward, turn around, don’t know |
| Turn left (2) | move left shoulder backward (3) | move/lift arm (2), lean left, lift shoulder |
| Turn right (2) | move right shoulder backward (3) | move/lift arm, lean right, lift shoulder, don’t know |

lated movements comprised the answers that resembled or contained the expected movements ($M = 21.11\%$, $SD = 18.48\%$). *Different movements* comprised the answers that differed from the expected results, such as conflicting movements or no movements at all ($M = 43.33\%$, $SD = 18.48\%$). Fig. 7.7 summarizes these responses. Table 7.6 lists all answers.

Instructions that intuitively represent body movements

The answers to directional lines delivered laterally to the torso (55.56%), laterally to the thighs (44.44%), and to the back of the thighs (44.44%) most often corresponded to their intended meaning. When also related movements were considered, lateral pulses at the thighs (89%) and rotation around the shoulder (55.56%) most often corresponded to their intended meaning. From this viewpoint, on average 5.64 ($SD = 2.07$) of the ten patterns could be considered to intuitively represent body movements.

On average, learning the instructions lasted around 4 minutes.

On average, the participants learned the mapping between the tactile patterns and their meaning for 3.44 minutes ($SD = 1.42$ minutes). The minimum learning time was two minutes. The maximum learning time was

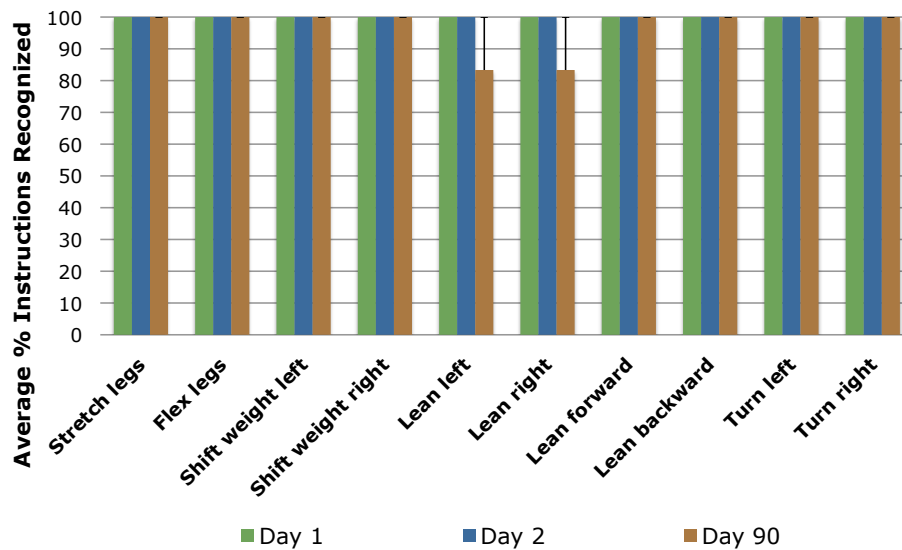


Figure 7.8: Average percentage of recalled tactile motion instructions on the first two days (nine participants) and three months after learning the instruction set (six participants, with standard error).

six minutes. Overall, these learning times corresponded to the observed learning times in our previous studies (see sections 6.3.1 and 7.2).

Fig. 7.8 shows which instructions the participants recalled. Six of the nine volunteers returned to participate in the long-term study that was conducted three months after learning the instruction set. On day 90, all participants correctly recognized all instructions except one participant who intuitively preferred a mixed metaphor. This participant preferred the pull metaphor for stimuli at the chest and at the back, and the push metaphor for lateral stimuli at the torso and the thighs. He recalled the meaning of the patterns that were applied laterally to the thighs but misinterpreted the patterns that were applied laterally to the torso.

All except one participant correctly recognized all instructions.

On the second day of the experiment, the participants rated the mapping between the patterns and their meaning. These comments comprised:

The instructions were considered as intuitive and as easy to learn.

- “The patterns for leaning to the left and to the right feel most intuitive.”
- “The patterns for turning the body represent the movements very good.”
- “They are easy to learn and to remember.”
- “The patterns are intuitive. Upper body rotation requires learning because the other patterns made me move away from feedback. It might be easier for me to switch the patterns at the shoulders.”
- “They are easy to learn but the mixed metaphor makes them harder

to learn. One metaphor might be easier for me. The duration of the patterns is quite long.”

- “The patterns are easy to learn. The patterns around the shoulder do not need the motor at the chest, which first enticed me to lean sideways. The two motors lateral at the shoulder and at the back are sufficient. I can remember the patterns well after one day. I also remember well new techniques in table tennis.”
- “The patterns are easy to learn, especially my intuitive responses. Directional lines and rotation are good. I do not like the motors to start and stop abruptly. They should be like a wave and increase gradually.”
- “Rotational patterns and patterns for leaning, which go upwards on the body, are good to follow and intuitive. Leaning forward and backward are less clear because they can be interpreted differently.”
- “The patterns are intuitive, easy to learn, and to internalize. It might be easier if all patterns showed the direction to move (pull) instead of being mixed. A mixed metaphor makes sense for single patterns.”

7.3.3 Discussion

Five instructions corresponded to the users’ intuitive reactions to the chosen tactile patterns.

The findings of this study confirmed that the intuitive responses to the same tactile pattern could vary between people, as was also the case in the initial investigation on the interpretation of tactile stimuli. This supports our assumption that tactile motion instructions are not universally intuitive. While some instructions were regarded as intuitive, the meaning of other instructions had to be learned. On average, our participants regarded five of the ten instructions as intuitive. They responded with the same body movements that these patterns were intended to convey.

The instructions can be learned quickly.

This does not mean that the mapping between the other five patterns and their meaning did not make sense. The participants’ comments indicated that these mappings were plausible as well, although they had to be learned. Even so, the average time that the participants spent to learn these mappings was around four minutes. Moreover, they could recall the meaning of all patterns after an extended time without practice in-between. These findings indicate that the designed tactile patterns were appropriate as instructions that represented body movements in an intuitive way.

Many intuitive reactions were similar and resembled the intended body movements.

The cut-off point between answers that we have classified as intended movements, related movements, and different movements is debatable. We have used a stringent classification scheme to reveal the number of answers that were associated with the expected body movements. Nevertheless, many of the other reactions corresponded to these movements for the most part. For example, we have differentiated between *lean backward*, *straighten up*, and *move the shoulders backward*, but these movements have something in common. Considering a less stringent viewpoint, for example by merging

intended and related movements in Fig. 7.7, this could explain why our volunteers regarded all instructions as easy to learn and intuitive.

The findings of this study corresponded to our initial findings on the intuitive interpretation of tactile stimuli (see Table 6.3). Apart from the semicircular lines around the shoulders, which seemed to be less expressive than directional lines around the waist or around both shoulders (see section 6.4), all patterns were similarly interpreted. Also, the directional lines that were applied to the front of the thighs in upward direction were associated with jumping a few times, but they were inexpressive otherwise.

This study did not include an active situation. The participants were not required to speak while moving the body or to interpret instructions that might have interfered with movements that they would have already performed during the physical activity. Since all instructions were recalled with optimal accuracy after an extended time, we could argue that our experimental conditions were the main reasons why our participants misinterpreted instructions in active situations, both in the laboratory on the Wii balance board and in the field while snowboarding and horseback riding. Nevertheless, we cannot confirm this assumption at this time because we do not have technology that could automatically classify body movements or that could provide instructions only when corrections are required.

Despite the fact that our user group correctly interpreted all instructions, the number of volunteers was low. Moreover, our user group only included a subset of potential users. With a larger sample size and with other age cohorts, the results might vary.

Regarding the encoding metaphor, we have found that five participants preferred a mixed metaphor that included instructions based on the push metaphor and instructions based on the pull metaphor (see also section 7.2). These participants did not mention to have difficulty in learning and remembering mixed mappings. Nevertheless, three of them stated that all instructions should be based on a consistent metaphor, which would make the set of instructions easier to learn and recall. Considering each instruction separately, however, the intuitive reactions would make sense.

Regarding the possible origins of the preferred encoding metaphor, some participants might have previously experienced natural tactile sensations that biased them to move in a particular direction, such as during sports training. Also, this preference might have been caused by the way that they interacted with other people, such as when they were pulled at the arm or pushed from the back. One participant mentioned that this preference could relate to the disposition of animals, which are either predators or prey. For example, horses are prey that respond to pressure by pushing back against pressure. This is their natural reaction to break loose of a predator's hold [Roberts, 1997]. In contrast, other prey animals pull away from pressure to escape. Humans might intuitively respond in similar ways to pressure, either by pushing into pressure or by pulling away from pressure.

In retrospect: The intuitive interpretation of tactile stimuli was similar across the different user groups

The experimental conditions likely caused misinterpretations in active situations.

The sample size was small.

Mixed metaphors are common.

Possible origins of the preference to being pushed or pulled

7.4 Closing Remarks

Tactile motion instructions establish a simple language.

In this chapter, we have first focused on the language aspect of tactile motion instructions. While a single instruction could represent a specific body movement, compound instructions that convey a sequence of messages could represent a sequence of body movements. Our findings revealed that young adults were able to perceive and to identify compound instructions with high accuracy in an active situation. Overall, this finding indicates that tactile motion instructions establish a simple language for physical activities, based on single and compound instructions that resemble words and sentences in spoken languages.

The push and the pull metaphor can be used for encoding messages.

Another topic of this chapter concerned tactile stimuli that represented a push or a pull of the body, in particular how stimuli that represented the user's counter-intuitive reaction—push instead of pull and vice versa— influenced the user's responses. We found that both encoding metaphors could effectively encode the messages of tactile instructions. Moreover, users who preferred to move either towards or away from the vibration could quickly learn to move in the opposite direction.

Some tactile motion instructions are intuitive, whereas some have to be learned.

Initially, we have based the designed set of tactile motion instruction patterns on the intuitive responses of young adults to artificial tactile stimuli. After evaluating these patterns in several user studies and modifying them based on the gained results, we have re-evaluated if young adults considered these patterns to intuitively represent the chosen body movements. On average, each participant regarded half of the designed patterns to intuitively represent these movements, whereas the meaning of the other patterns was less obvious because they associated these patterns with different body movements. Even so, our participants regarded all instructions as plausible, and they could quickly learn and recall the meaning of the patterns after an extended time.

Learning of motor skills

Our work so far has shown that artificial tactile stimuli could be applied as instructions in active situations. In the next chapter, we will focus on learning of motor skills. We will report a field study where we have applied tactile motion instructions in a realistic situation during sports training.

Chapter 8

Learning Motor Skills

“I now realize that the small hills you see on ski slopes are formed around the bodies of forty-seven-year-olds who tried to learn snowboarding.”

—Dave Barry

Our previous investigation into tactile motion instructions addressed their design, perception, and learning. We have shown that young adults could perceive and recognize ten instructions with high accuracy in active situations. Moreover, they could quickly learn and remember these instructions after several weeks. To complement our research, we will now focus on learning of motor skills. We will report the results of a field study that has investigated if tactile motion instructions could support snowboarders in practicing an unfamiliar riding technique, as envisioned in chapter 1.

Tactile motion instructions applied to snowboard training

The study reported here not only reached into an area that is of interest to sport scientists but also went beyond current practice. In many sports, it is impractical to provide feedback on performance during exercises. For this reason, researchers typically investigated the influence of concurrent feedback on an athlete’s performance and learning of motor skills in constrained settings, such as in the laboratory, using feedback that athletes received on a computer monitor while moving the body. Moreover, tactile motion instructions, which represent specific body movements, have not been explored before. Our study provided the first insights into using this novel approach for teaching motor skills in a real-world setting, based on our custom-built wearable system that could automatically signal snowboarders which body movements to perform while descending the slope.

We broke new ground in research on motor learning.

Before detailing this experiment and the results, we will briefly summarize important factors that could influence how well humans can perform and learn motor skills. These issues explain the design of our study and the implications of our findings in the larger context of motor learning.

8.1 Feedback in Motor Skill Learning

Intrinsic and extrinsic feedback

Two types of feedback are distinguished in the field of motor learning: *intrinsic* and *extrinsic* feedback [Winstein, 1991]. Intrinsic feedback relates to information that athletes naturally perceive while performing movements. This includes kinesthetic information on the position and movements of the limbs, derived from receptors inside muscles and joints. Extrinsic feedback, also called augmented feedback, relates to information that coaches provide in addition to intrinsic feedback. This feedback could be provided concurrently while performing movements, immediately following, or delayed after performing movements. In contrast to feedback, *feedforward* is information provided before performing movements [Winstein, 1991].

Knowledge of results and knowledge of performance

Extrinsic feedback comprises *knowledge of results* and *knowledge of performance* [Winstein, 1991]. Knowledge of results describes how successful the task was performed compared to the desired outcome. Examples include statements such as “Well done” or the time that was required for performing the task. Knowledge of performance addresses the movement patterns and describes how to correct the posture or how to move the limbs. Examples include statements such as “Flex the legs a little more” or the deviation in degrees of the performed movements from the intended movements.

Extrinsic feedback is important for learning motor skills.

Various studies have been conducted that focused on how extrinsic feedback could influence the performance and learning of motor skills. In general, extrinsic feedback is considered important because it guides the learner to the correct movements during the following trials [Winstein, 1991, Wulf, 2007]. Even so, many studies that have addressed the effects of the frequency of extrinsic feedback have lead to controversial results. While some researchers reported that learners could benefit from frequent feedback [Bilodeau and Bilodeau, 1958, Bilodeau et al., 1959], others argued that too much feedback could have negative consequences [Salmoni et al., 1984]. We will briefly summarize the main arguments as reported in [Wulf, 2007].

Frequent feedback could decrease the performance and could hinder the learning of motor skills.

According to the *guidance hypothesis* [Salmoni et al., 1984, Schmidt, 1991], feedback guides the learner to the correct movements. Even so, frequent feedback has two disadvantages. First, the learner could neglect the intrinsic feedback and could become dependent on the extrinsic feedback. As a result, the performance could deteriorate after feedback is withdrawn. Second, frequent feedback could hinder the learner in developing a stable representation of the movements because it prompts to correct even small errors that might have been caused by the variability in the motor system.

Concurrent feedback could block the processing of intrinsic feedback.

Concurrent feedback has been shown to have strong guiding effects that increase the performance during practice but that block the processing of intrinsic feedback [Wulf, 2007]. This could decrease the performance when no feedback is provided, such as in retention tests [Park et al., 2000]. Overall, to decrease the dependency on feedback that is provided frequently or concurrently, its frequency should be reduced, for example, by providing feedback only in every second trial [Park et al., 2000, Wulf, 2007].

The *constrained-action hypothesis* [Wulf et al., 2001] offered new insights into this topic. This hypothesis states that the wording of feedback guides the learner's attention during the execution of movements and influences the performance and learning of motor skills. Focusing on the movements (*internal focus*) disrupts automatic control processes that would normally regulate the movements effectively and efficiently. In contrast, focusing on the effects of the movements (*external focus*) supports unconscious and reflexive processes that automatically control the movements. For this reason, athletes should not try to actively control their movements.

The wording of feedback influences the performance and learning of motor skills.

For example, the instruction *Flex the legs* would induce an internal focus. As a result, the athlete would pay attention to consciously flex the legs, which would constrain automatic processes that would normally regulate knee flexion. In contrast, the instruction *Crouch* would induce an external focus. The athlete would not pay attention to consciously flex the legs. As a result, the motor system would respond unconsciously, which would enhance performance and learning.

An external focus does not hinder automatic control processes.

The assumption that the wording could influence performance and learning has led to studies on the effect of attentional focus. For example, Shea and Wulf [1999] investigated how accurately participants could balance on a stabilometer platform, which required them to redistribute the weight evenly between the feet in order to keep the platform horizontally, depending on whether or not they received concurrent feedback on a computer screen. This feedback represented the deviation from a balanced position, considering internal and external focus instructions. In another study, Wulf et al. [2002] measured how accurately novices and advanced volleyball players could perform serves depending on the wording of instructions, and how accurately advanced soccer players could perform lofted passes depending on the frequency and wording of instructions. Overall, the findings indicated that feedback and instructions improved the performance and learning of motor skills if they promoted an external focus of attention. Moreover, frequent and concurrent feedback did not hinder learning.

Frequent and concurrent feedback or instructions do not hinder learning if they promote an external focus of attention.

The majority of studies that have investigated how the wording of feedback influenced the performance of motor skills have addressed *closed skills*. These skills involve body movements that are performed in a stable environment where the environmental conditions do not change. Also, the athlete can decide when to execute the movements, such as when playing golf. In contrast, *open skills* involve body movements that are executed under time pressure without planning them. Moreover, the environmental conditions could change while performing the movements, such as when the opponent influences the trajectory of the ball in soccer or tennis matches.

Closed skills and open skills

So far, only few studies have explored how the wording of feedback could influence the performance of open skills. For example, Maddox et al. [1999] measured the accuracy of tennis backhand strokes on balls played with variable trajectories. The results suggested that external focus instructions could improve the performance of athletes. Even so, more studies are required to confirm the constrained-action hypothesis for open skills.

External focus instructions for open skills

8.2 Concurrent Tactile Motion Instructions for Learning Motor Skills in Snowboarding

We have focused on concurrent feedback for open skills in a real-world setting.

Since the missing realtime feedback on performance while snowboarding originally motivated us to design tactile motion instructions, we have decided to test these instructions in this particular context as an example. Snowboarding is an interesting and a challenging physical activity for studying concurrent feedback and instructions. This activity involves open skills because snowboarders move in an unstable environment. They have to quickly decide when and where to perform turns, and how to move the body. The movements of the board in the snow, the descents of other skiers and snowboarders, and environmental forces, including snowfall, wind, and solar radiation, continually change the characteristics of the slope. From the perspective of research in motor learning, we have focused on concurrent feedback, on knowledge of performance, and on open skills that are performed under real-world conditions.

The wearable sensing technology influenced the design of the study.

Two issues have influenced the design of our study and the motor task that we have investigated. First, we were looking for a wearable system that could automatically provide tactile motion instructions on riding mistakes. Since we did not have technology that could detect mistakes, we have built a system that could sense the riding edge (see chapters 3 and 4) and that could provide instructions for guiding the snowboarder to the correct body movements during turns. This experimental setup was similar to other studies in motor learning [Wulf, 2007], where athletes did not receive feedback on mistakes but instructions how to perform a motor task.

First-time snowboarders were too inexperienced to participate.

Second, we were looking for participants with the same skill sets. First-time snowboarders who did not have skills in snowboarding would have been ideal candidates because it would have been possible to compare their learning progress and to draw conclusions on the effects of tactile motion instructions. Novices, however, would have needed introductory lessons in order to gain the skills that were required for learning how to perform turns, such as sliding on the edge and turning towards the fall line. Also, beginners fall frequently. Since snowboarders need to perform a few turns to gain speed, to accommodate to the slope, and to find a safe riding style depending on their skills, frequent falls would have prevented them from experiencing automatic instructions at regular intervals during the ride.

Advanced beginners as participants

Considering these issues, advanced beginners were more appropriate candidates for studying the effects of tactile motion instructions on motor skill learning. Even so, advanced beginners have different riding skills. This made it difficult to find a motor task that challenged all snowboarders and that allowed to compare their learning progress.

We decided to teach advanced snowboarders how to ride basic turns *switch*.

In order to balance the need for experienced candidates who could descend the slope without frequent falls and for finding a motor task that also challenged these riders, we have decided to teach advanced beginners how to ride basic turns *switch*. Snowboarders prefer to ride either with the left

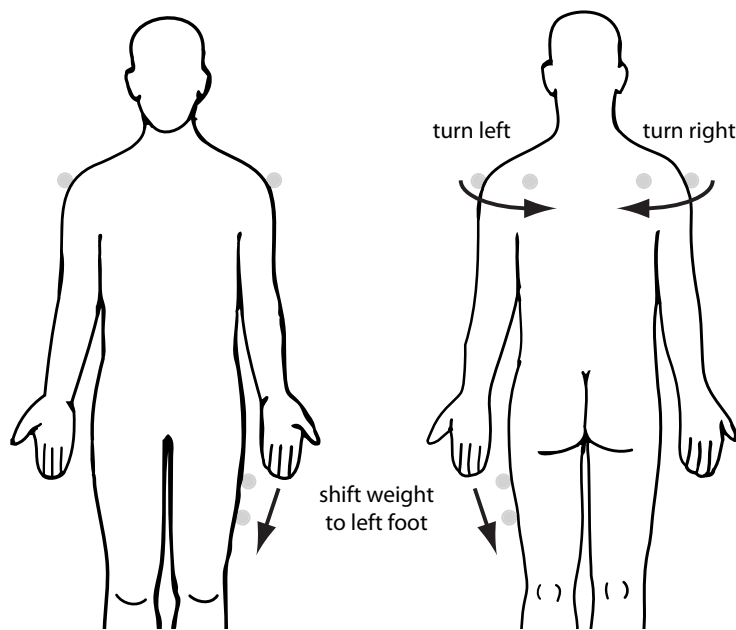


Figure 8.1: Two vibration motors were placed around each shoulder and laterally at the thigh that pointed forward while riding switch. The arrows indicate the direction of the evoked sensations.

foot or with the right foot pointing forward (see Fig. 4.1). This preference in the stance is similar to being left-handed or right-handed. When riding switch, the foot that would normally point backward points forward. This posture would make even experienced riders feel clumsy like beginners.

The correct technique for basic turns involves a sequence of different body movements (see section 4.2). The rider has to shift the weight to the front foot and to rotate the upper body towards the new riding direction (see Fig. 4.3 (b)). The resulting posture would lead the board to follow these movements, to align to the fall line, and to pivot to the other edge. After pivoting, the rider has to return to neutral position by redistributing the weight evenly between both feet and by aligning the upper body parallel to the board.

Correct posture
for basic turns

This sequence of movements challenges many snowboarders and often results in two common snowboarding mistakes: incorrect weight distribution and counter-rotation (see Fig. 4.4). Facing downhill, many riders are afraid to shift their weight towards the front of the snowboard. Instead, they keep their weight towards the back foot. This posture makes it difficult to turn the board and could lead to falls. Also, many riders do not properly align their torso towards the new riding direction. As a result, they abruptly turn their upper body for pivoting the board by exerting force.

Proper weight
distribution and
upper body
rotation challenge
many
snowboarders.

We have applied two tactile motion instructions as compound instructions to address these mistakes. Fig. 8.1 illustrates these instructions for a snowboarder whose left foot pointed forward while descending the slope. Con-

Compound
instructions
reminded of
correct posture.

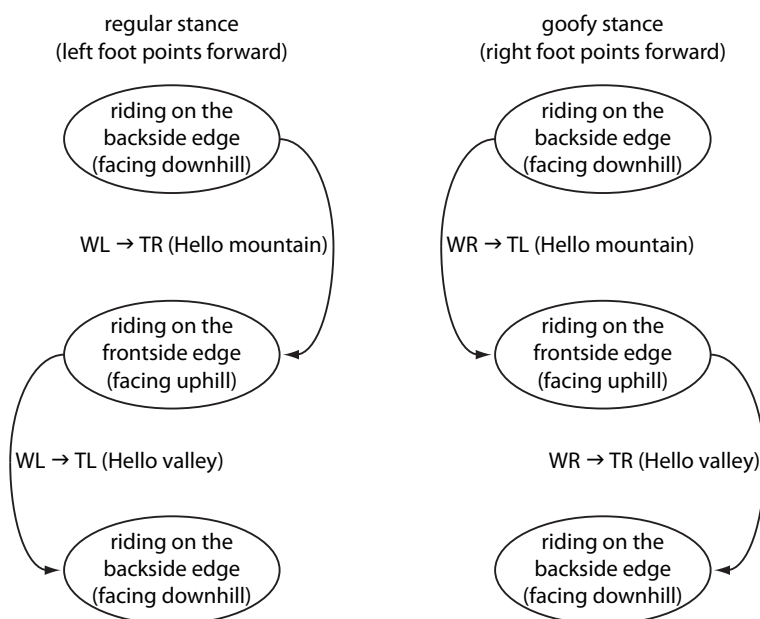


Figure 8.2: Tactile motion instructions for regular and goofy stance (see also Fig. 4.1 for the stance and Fig. 4.3 for the correct posture).

Considering the pull metaphor, the first instruction stimulated the left thigh and prompted to increase the weight towards this foot. The second instruction stimulated the shoulder that corresponded to the new riding direction (left or right) and prompted to turn the upper body accordingly. Although our wearable system could not predict the instant when a snowboarder intended to begin a turn, the system could provide these compound instructions when the snowboard pivoted from one edge to the other edge (see section 4.4.3). This allowed the participants to descend at their own pace and to receive tactile instructions while pivoting the snowboard.

The instructions were worded to promote an external focus of attention.

We have mentioned that instructions and feedback on performance should guide the learner's attention to the effects of body movements instead of to the body (see section 8.1). Since the original meaning of our instructions described body movements, their wording had to be changed to induce an external focus of attention (see also Table 6.7). The lateral vibration at the left (right) thigh, which could convey the message *Shift your weight to the left (right) foot*, was reworded to $WL/WR = \text{Increase the pressure towards the nose of the snowboard}$. The vibration around the left (right) shoulder, which could represent *Turn your upper body to the left (right)*, was reworded to $TL/TR = \text{Hello mountain}$ or $TL/TR = \text{Hello valley}$. These alternative wordings for TL and TR —mountain or valley—depended on the riding direction, which could be towards the left or right side of the slope, and whether the new turn was performed on the frontside or backside edge. This relationship is explained the following two paragraphs (see Fig. 8.2).

The instruction set for regular stance

For a rider whose left foot pointed forward (regular stance) and who started to descend on the backside edge towards the left side of the slope, facing downhill, a subsequent switch to the frontside edge towards the right side

of the slope, facing uphill, first stimulated the left tight, then the right shoulder: $WL \rightarrow TR$ ($TR = \textit{Hello mountain}$). The next switch to the backside edge towards the left side of the slope, facing downhill, stimulated the left tight and the left shoulder: $WL \rightarrow TL$ ($TL = \textit{Hello valley}$).

For a rider whose right foot pointed forward (goofy stance) and who started to descend on the backside edge towards the right side of the slope, facing downhill, a subsequent switch to the frontside edge towards the left side of the slope, facing uphill, first stimulated the right tight, then the left shoulder: $WR \rightarrow TL$ ($TL = \textit{Hello mountain}$). The next switch to the backside edge towards the right side of the slope, facing downhill, stimulated the right tight and the right shoulder: $WR \rightarrow TR$ ($TR = \textit{Hello valley}$).

The instruction set for goofy stance

Up to now, however, the effect of the wording of feedback on the performance of motor skills has not been explored for tactile instructions that stimulated the body. This raised the question if artificial tactile stimuli could negate the effect of the intended wording, thereby causing an internal focus of attention. We surmised that these stimuli would not induce an internal focus because responding to tactile motion instructions seemed to resemble a knee-jerk reaction that happened automatic. Similar to turning around upon perceiving a tap at the shoulder, we surmised that the sensation that a tactile instruction evoked was associated with the conveyed message and not with the stimulated body area.

Tactile instructions and external focus of attention

8.3 Experimental Setup

In this study, we have explored if tactile motion instructions that were applied concurrently while descending the slope could support snowboarders in learning an unfamiliar riding technique. The hypotheses were:

We hypothesized that tactile instructions will reduce riding mistakes.

- Alternative hypothesis: Snowboarders will make fewer mistakes when they ride with tactile motion instructions than when they ride without these instructions.
- Null hypothesis: The number of mistakes that snowboarders make will not be lower when they ride with tactile motion instructions than when they ride without these instructions.

The experiment took place on a slope of 520 m (1700 ft) length in the indoor ski resort SnowWorld Landgraaf, The Netherlands. One instructor from the SNOW SPORT Team of RWTH Aachen University volunteered to conduct a one-day snowboarding course. He taught how to ride basic turns switch. This technique required the participants to descend in an unfamiliar posture: the foot that normally pointed backward on the snowboard pointed forward. Regular riders who preferred to descend with the left foot pointing forward became goofy riders who had to descend with the

The participants learned to ride switch.

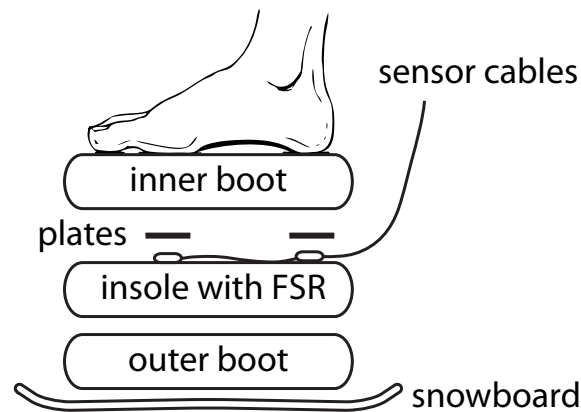


Figure 8.3: The insoles with two force sensors were placed between the inner and the outer boot to increase comfort.

right foot pointing forward. Goofy riders became regular riders who had to descend with the left foot pointing forward (see Fig. 4.1).

8.3.1 Hardware Setup

We replaced the backpack with a small pouch worn at the waist.

The participants wore our custom tactile suit (see Fig. 6.4) with six vibration motors, as illustrated in Fig. 8.1. To increase the perceived intensity of the tactile stimulations, they wore these clothes inside out such that the motors were slightly pressed against the skin. Since some of our previous volunteers did not like to wear a backpack (see sections 6.3.2 and 6.3.3), we have decided for using a small pouch (see Fig. 4.10, right), which was carried around the waist, and for one SensAct box (see Fig. 3.5). The host device, a Nokia N70 mobile phone that controlled the box, was inserted in a pocket of the participants' jackets.

Each tactile pattern activated two motors.

Since our SensAct box only had connections for six motors, we had to reduce the number of motors per tactile pattern from three to two (see Fig. 8.1). Overall, this restriction did not degrade the indented tactile experience because two stimulation points are at least required in order to display directional lines based on sensory saltation (see section 5.3).

Two force sensors captured the weight distribution.

The wearable system had to sense the riding edge for detecting the instant when the rider pivoted the snowboard (see section 4.4.3). This required us to use two force sensors per foot, which measured the weight distribution under the heel and under the ball of each foot. To prevent the participants from feeling the sensor cables under their feet, we attached the sensors to felt insoles, 0.5 cm thick, and placed them between the inner and the outer boot (see Fig. 8.3). Since we expected that this layering could dampen the measured forces, which could decrease the system's accuracy in classifying the riding edge, we placed a thin plastic plate, 3 × 5 cm wide and 0.1 cm thick, between each sensor and the insole. These plates transferred the forces that occurred around the small sensors to these sensors' active areas.

The program for classifying the riding edge and for triggering the tactile instructions was distributed across our wearable platform (see Fig. 3.1). The SensAct box sampled sensor data and classified the riding edge. When the riding edge changed, the result was time-stamped and transmitted to the host device. Depending on the riding edge and stance, a Python script running on the host triggered the appropriate compound instruction, and logged this instruction with its own time stamp.

The program was distributed across both devices.

In our previous field study on the slope (see section 4.4), the SensAct box sampled and streamed force sensor data at 50 Hz. At this sampling rate, however, the ATmega168 micro-controller of the Arduino BT built inside the SensAct box (see Fig. 2.2, right), which classified and streamed the riding edge to the host in realtime, processed the commands that activated the vibration motors too slowly. The burst duration and the pauses between consecutive pulses increased significantly, which hampered the tactile experience. Moreover, the system reported new turns too late.

Slow micro-processor inside the SensAct box

To keep the system responsive, we lowered the sampling rate. We found 10 Hz to yield an adequate processing speed that allowed the micro-controller to sample force sensor data, to classify the riding edge, to send the result to the host, to process the received commands, and to render the intended tactile sensations in time.

10 Hz sampling rate

The following lines show an excerpt from the host device's data log files recorded during the study. The box transmitted the time-stamped riding edge (timestamp in ms; 5 = pivoting, 14 = frontside edge, 16 = backside edge). The host logged the posture that represented the snowboarder's current turn (Hello mountain, Hello valley, goofy stance, timestamp).

```
2561544;5
2561644;14
Hello mountain goofy at 11-33-49
2570900;5
2571100;16
Hello valley goofy at 11-33-58
2583864;5
2583964;14
Hello mountain goofy at 11-34-11
2596308;5
2596508;16
Hello valley goofy at 11-34-24
2607576;5
2607776;14
```

8.3.2 Pilot Test with Snowboard Instructor

Before conducting the study, a pilot test revealed the strengths and limitations of our wearable sensing and feedback system. The snowboard instruc-

The snowboard instructor tested the wearable system.

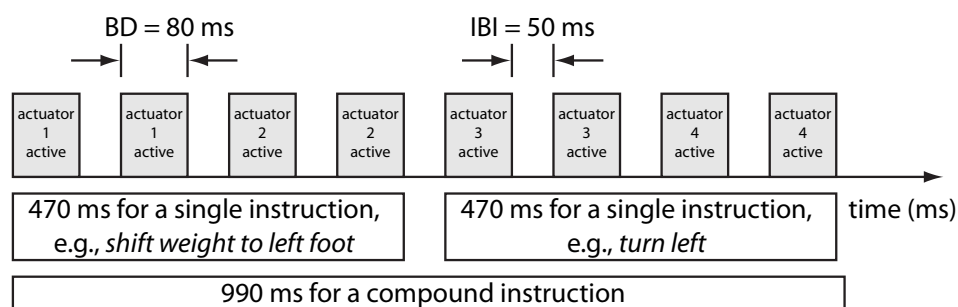


Figure 8.4: The reduced timing values for tactile motion instructions that based on directional lines, as illustrated in Fig. 8.1.

tor tested the hardware on the same slope where we intended to conduct the experiment. To experience when the tactile instructions were triggered during descents and how this feedback felt during the ride, he varied the speed and switched between different riding techniques, including basic turns, wide and short turns, carving, and riding switch. His insights helped us to gauge how well the system would respond to the different riding skills of potential candidates who would participate in the study. Also, we received feedback on the composition of the tactile patterns, which allowed us to adjust the timing values for improving the tactile experience.

Tactile instructions were too long.

The instructor noticed that the compound instructions were too long. During short turns, they did not match to the movements that the snowboarder had to perform after pivoting the board—returning to neutral position (see sections 4.2 and 8.2). Sometimes, they also interfered with the body movements that introduced the next turn.

We reduced the duration of compound instructions to 990 ms.

The length of a single instruction was 850 ms, which sequentially pulsed two motors for three times, based on our standard timing values (100 ms for bursts, 50 ms for pauses between bursts). The compound instructions lasted 1750 ms. To shorten the length of the tactile patterns, we explored in a self-experiment how fewer pulses per motor, shorter pulse durations, and shorter pauses between consecutive pulses altered the perceptions on the skin. We agreed to pulse each motor twice, as at least two pulses per actuator are required for sensory saltation (see section 5.3), and to maintain the pauses between the bursts at $IBI = 50$ ms, which is the optimal timing value for sensory saltation (see section 5.3). In addition, we lowered the burst duration to $BD = 80$ ms. These timing values preserved the intended tactile experience and reduced the length of a single instruction to 470 ms. The duration of the compound instructions was 990 ms (see Fig. 8.4).

The system correctly recognized turns, but tactile instructions for backside turns were slightly delayed.

The instructor reported that he basically perceived instructions during all turns, which confirmed that our system could detect turns in realtime with the new sensor layering, with reduced sampling rate, and independent of the riding speed, riding technique, or edging angle. He stated, however, that although he received instructions at the very moment when pivoting the board to the frontside edge, he received instructions shortly after pivoting the board to the backside edge. Ideally, the instructions should have

occurred at the very moment when the body movements were required. This was while initiating the turn and while pivoting the snowboard. Even so, he considered these slightly delayed instructions as less likely to disturb or to misguide our participants if we shortened the duration of the patterns to prevent feedback while traversing the slope after pivoting the board.

The reason why feedback was delayed during backside turns could relate to the front binding and to the threshold value T_E , which yielded the riding edge (see section 4.4.3). The front strap of the binding fixated the front part of the boot. During backside turns, with increased weight towards the heels, the frontside edge did not touch the slope. Even so, when the toes were pulled upwards, the ball of each foot remained in its position, and the force sensors still measured some pressure. The difference in weight distribution between the ball of each foot and the heels fell below the threshold value once the rider exerted more pressure on the heels. This typically occurred after pivoting the board, which could have slightly delayed the recognition of backside turns. In contrast, the force sensors located under the heels did not measure pressure during frontside turns when the weight was towards the ball of each foot. In this case, the rider could freely lift the heels inside the boots, which yielded a quick response to frontside turns.

To increase the system's responsiveness and to decrease the delay of instructions during backside turns, we lowered the threshold value T_E . A lower value made the algorithm more sensitive to weight shifts. This threshold value, however, has to be carefully chosen because the system could misclassify turns during bumpy rides with low thresholds (see section 4.4.3).

8.3.3 Participants

The experiment was conducted on five consecutive Fridays. For each day, two snowboarders were recruited over e-mail with help from the local university's sports center. These volunteers had to spend almost the entire day in the ski hall (9:00–15:00). Two women and eight men aged 21–29 years ($M = 26.10$) participated.

It was not possible to recruit only snowboarders with similar riding skills. A few volunteers canceled their appointment on short notice such that we had to resort to volunteers who had time to participate. On a scale ranging from level one (beginner) to level five (expert), three participants rated their skills in snowboarding as level one, four as level two (advanced beginner), and three as level three (advanced). On average, they snowboarded for 4.2 years ($SD = 3.6$ years) and between one and three weeks per year. Three volunteers had previously participated in a snowboarding course to improve their riding skills. Six volunteers had previously tried to ride switch. Three volunteers had participated in our studies on vibrotactile feedback. All candidates also practiced other sports occasionally, including biking, jogging, surfing, horse riding, tennis, rowing, and ball games.

The snowboard binding influenced the force sensor measurements and the classification results.

A low threshold value increased the system's responsiveness.

The study lasted one day and was repeated over five weeks. Ten users participated.

Nine participants had snowboarded before; six had already tried to ride switch.

One first-time snowboarder participated.

One of these volunteers was a first-time snowboarder. The instructor had to introduce her to the basics of snowboarding. She practiced how to correctly fall and how to slide on one edge. She also tried basic turns, riding with her preferred foot pointing forward. This introductory course lasted one hour.

8.3.4 Experimental Procedure

Four people accessed the ski slope on each day of the experiment: the snowboard instructor, two participants, and one assistant. The assistant set up the wearable system and videotaped the descents.

The binding was inversely mounted for riding switch.

The participants used snowboards with the binding inversely mounted to their preferred riding stance. Donning and testing the wearable system on level ground lasted one hour. After this setup phase, the group descended the slope once to warm up.

We have chosen a within-subjects design with two experimental conditions:

1. Traditional lessons with spoken instructions (feedforward) issued before each descent and with spoken feedback after each descent. These lessons served as control condition.
2. Lessons with spoken instructions issued before each descent, with automatic tactile motion instructions while descending the slope, and with spoken feedback after each descent.

Each condition comprised four descents. Overall, the participants descended ten times in this order:

- One descent for reference
- Four descents for one condition
- Four descents for the other condition
- One descent for reference

The first five descents were scheduled for the morning. The other five descents were scheduled for the afternoon, following a lunch break of 45 minutes. These descents are detailed below.

The instructor rated the participants' initial and acquired riding skills.

The first descent in the morning and the last descent in the afternoon served for rating the participants' initial skills in riding switch before the course and their acquired skills after the course. The participants did not receive spoken instructions before or spoken feedback after these trials. Neither did they receive tactile instructions while descending the slope. For fine-grained ratings, the instructor preferred a scale that ranged from very bad (1) to very good (10).

The snowboarding course was conducted during the following eight descents. In the morning, one participant (*S1*) was randomly chosen to descend without tactile instructions (condition 1). The other participant (*S2*) descended with tactile instructions (condition 2). During the four descents after the break, participant *S1* received tactile instructions (condition 2), whereas participant *S2* did not receive tactile instructions (condition 1).

Counterbalanced experimental conditions in the morning and afternoon

To prevent bias on the course instructor's part, we decided for a blind experiment. The instructor did not know during which descents the participants received tactile motion instructions, or if they received these instructions at all. Moreover, both participants wore the wearable system during all descents. This setup ensured that he treated all participants alike when teaching how to ride switch, when explaining exercises, and when providing spoken feedback on their performance after descending the slope. Unlike the instructor, the assistant knew which participant received tactile instructions. Before each descent, he operated both host devices to enable sensor data logging and to either enable or disable automatic feedback.

The course instructor did not know which participant received tactile instructions.

At the beginning of the course, the instructor introduced his students to neutral position. He explained how to perform turns for riding switch and demonstrated the required body movements while standing still. He mentioned that tactile motion instructions during descents indicated the correct weight distribution and the correct upper body rotation for pivoting. Vibration laterally at the thigh that pointed forward signaled to increase the pressure towards the front of the snowboard. Vibration at the left or right shoulder signaled the direction to turn the torso, which was either towards the mountain or towards the valley. The assistant manually triggered the corresponding compound instructions until both participants were sure to have memorized the meaning that these instructions represented.

Both participants learned the instructions at the start of the course.

For each of the four runs in the morning, the instructor issued an exercise. He explained and demonstrated the required movements on level ground at the top of the slope, and slowly descended the first half of the slope to demonstrate this exercise. He then waived at the first candidate to descend and to repeat this exercise up to the location where he was waiting. Having informed this participant on his performance and how to improve the riding technique, he observed and advised the second participant. Afterwards, the group descended the remaining half of the slope. This time, however, the instructor did not correct his students, which was similar to real courses where instructors cannot provide feedback after every run. Even so, participant *S2* did receive tactile instructions until the end of the slope.

The instructor explained and issued exercises, observed the participants, and provided feedback after descents.

The course continued after the lunch break. The instructor re-explained the meaning of the tactile instructions, and the assistant manually triggered the corresponding compound instructions. The following four runs resembled the lessons in the morning: the instructor explained and demonstrated new exercises, observed the participants during descents, and provided feedback on their performance after the first half of the slope. In contrast to lessons in the morning, participant *S1* received tactile instructions while descending the slope, whereas *S2* did not receive concurrent instructions.

The course continued in the afternoon.

The assistant videotaped the descents.

During the course, the assistant descended about 230 meters and stopped at the edge of the slope, above the instructor's observation point. He videotaped the participants from this location. At the end of the slope, he operated both host devices to save the logged sensor data files. Also, he paused the application, which prevented unintentional feedback while walking or waiting for the lift.

Experienced participants also practiced exercises that were more demanding.

During this five-week study, all participants practiced the same exercises in the morning. Advanced snowboarders, however, soon started to feel under-challenged after a few descents. For this reason, the instructor issued for these advanced riders exercises that were more demanding in the afternoon. For example, he asked them to increase the edging angle of the snowboard, as required for carved turns. The carving technique, however, also requires the snowboarder to descend at higher speed, to flex the legs, to keep the torso parallel to the board, to evenly distribute the weight between the left and right foot, and to pivot while traversing the slope before passing the fall line. In this case, the tactile instructions that indicated correct posture for basic turns would not guide the snowboarder to the posture and body movements for carving. For this reason, the instructor asked these riders to regard the instructions as a reminder for avoiding incorrect weight distribution and counter-rotation, which could also occur in carving.

A questionnaire gathered the participants' opinion.

At the end of the course, the participants answered a questionnaire (see Appendix D). This questionnaire addressed their previous experience in snowboarding, their view on riding switch, and their opinion on tactile motion instructions for learning to snowboard.

8.4 Results

Data analysis did not include the first turn and the last few turns of each descent.

Snowboarders often do not pay attention to their riding technique during the first and last few turns. At the beginning, they gain speed, whereas they lower their speed towards the end to stop safely. Therefore, we skipped the first turn and assessed the participants' progress in riding switch up to the point where the camera was positioned. The assistant videotaped the descents from approximately 25 meters above the instructor's observation point such that the participants decelerated after passing the camera.

8.4.1 Classification of the Riding Edge

We compared the sensor logs to the footage.

We have analyzed the sensor recordings and the footage in order to determine how accurate our wearable sensing system could classify the riding edge. The host devices that controlled the SensAct boxes were time synchronized with the video camera to log time stamps at one-second accuracy. Despite this coarse resolution, these time stamps allowed us to estimate the time offset between the instant when a new turn was started and when the instructions were perceived. Unfortunately, we had to exclude three partic-

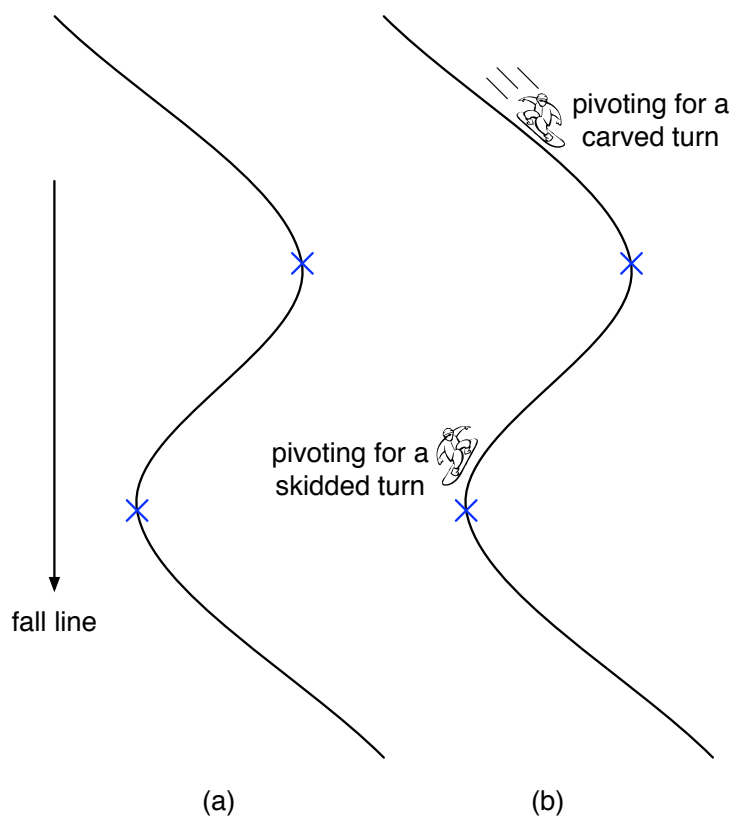


Figure 8.5: (a) The crosses indicate the turning points on the rider's path, which we marked on footage to count the number of turns and to estimate the point in time when our system triggered tactile instructions. (b) The quality of turns can vary during descents. When descending at high speed, skilled snowboarders could increase the edging angle to pivot their board to the other edge before passing the fall line (carved turn). Less skilled snowboarders would typically descend slowly and pivot with a low edging angle shortly before or when passing the fall line (skidded turn).

ipants from this analysis. A software bug had corrupted the host devices' time stamps on the first day, and one device was incorrectly synchronized with the clock of the camera on the last day. Nevertheless, these three participants did receive tactile instructions during the corresponding descents.

Our turn detection algorithm recognized new turns and triggered instructions when the difference in the weight distribution between the toes and heels exceeded the specified threshold value (see section 4.4.3). This occurred when the snowboarder redistributed the weight between the toes and heels while pivoting the board from one edge across the fall line to the other edge. On footage, however, the high uphill recording distance (200 meters) and continuously changing viewing angles on the riding paths often concealed the instant when the board was pivoted. Therefore, we marked the locations when the participants passed the fall line during turns, which we could clearly identify (see Fig. 8.5 (a)). In general, these turning points coincide with the instant when the board pivots to the other edge, otherwise the rider would not be able to change the riding direction.

Turning points on the riding path identified new turns.

Table 8.1: (a) T_1 and T_2 denote the average percentage of correctly classified turns during descents without and with tactile instructions. Three participants were excluded from this evaluation due to incomplete data log files. (b) O denotes the time offset between passing the fall line and the system triggering instructions (mean and standard deviation in seconds). A negative value indicates that the instructions were triggered before passing the fall line as observed on footage. (c) D denotes the duration of turns when riding with tactile instructions as observed on footage (mean and standard deviation in seconds).

| | Participant | <i>A</i> | <i>B</i> | <i>C</i> | <i>D</i> | <i>E</i> | <i>F</i> | <i>G</i> | <i>H</i> | <i>I</i> | <i>J</i> |
|---|-------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| a | T_1 | – | – | 100 | 66.7 | 100 | 91.9 | 47.4 | 100 | – | 100 |
| | T_2 | – | – | 100 | 87.0 | 100 | 100 | 51.6 | 100 | – | 100 |
| b | $M(O)$ | – | – | 0.2 | -0.3 | -0.1 | 0.6 | -0.2 | 0.2 | – | -1.6 |
| | $SD(O)$ | – | – | 0.9 | 1.9 | 0.9 | 0.8 | 1.5 | 0.9 | – | 0.6 |
| c | $M(D)$ | 5.9 | 3.3 | 12.2 | 4.1 | 7.7 | 4.8 | 6.4 | 6.5 | 4.9 | 4.4 |
| | $SD(D)$ | 1.2 | 1.1 | 4.4 | 1.2 | 1.7 | 1.3 | 2.7 | 2.0 | 1.5 | 0.8 |

90.97% of all turns were recognized.

The participants performed on average 7.44 turns ($SD = 2.01$, $min = 4$, $max = 14$) while riding switch from the top to the middle of the slope. The algorithm correctly classified 90.97% of these turns. The descents without tactile instructions comprised on average 7.68 turns ($SD = 2.38$, $min = 4$, $max = 12$); 90.19% have been recognized. The descents with tactile instructions comprised on average 7.15 turns ($SD = 1.54$, $min = 5$, $max = 11$); 90.67% of these turns have been recognized. While the participants *C*, *E*, *F*, *H* and *J* received instructions during all turns, the sensing system worked less accurately for *D* and *G*, who received instructions in 87.0% and 51.6% of their turns (see Table 8.1 (a)). Overall, the sensing system missed less than 10% of turns. For these turns, tactile motion instructions have not been triggered. Also, we found one false positive.

On average, our system triggered instructions when the participants passed the fall line as observed on footage.

The average difference between the time stamps of the sensor logs and the time stamps of the turning points on footage indicates that tactile instructions coincided with the time when the participants passed the fall line (in seconds: $M = -.2$, $SD = 1.2$). These times, however, varied across the participants. For example, *F* received instructions on average 0.6 seconds after passing turning points, whereas *J* received instructions 1.6 seconds before passing turning points (see Table 8.1 (b)). The reason why these time offsets varied is that the turning points on footage did not always coincide with the time when the board was pivoted to the other edge. Snowboarders could switch to the other edge at different points in time before passing the fall line, which could depend on their riding skills, edging angle, riding style, and riding speed (see Fig. 8.5 (b)).

One participant received delayed instructions.

To illustrate the point in time when the participants perceived tactile motion instructions, we have calculated the average duration of the turns (see Table 8.1 (c)), based on the time between two turning points as observed on footage (see Fig. 8.5 (a)). Fig. 8.6 illustrates these average durations and the period when the participants likely perceived the instructions. Overall,

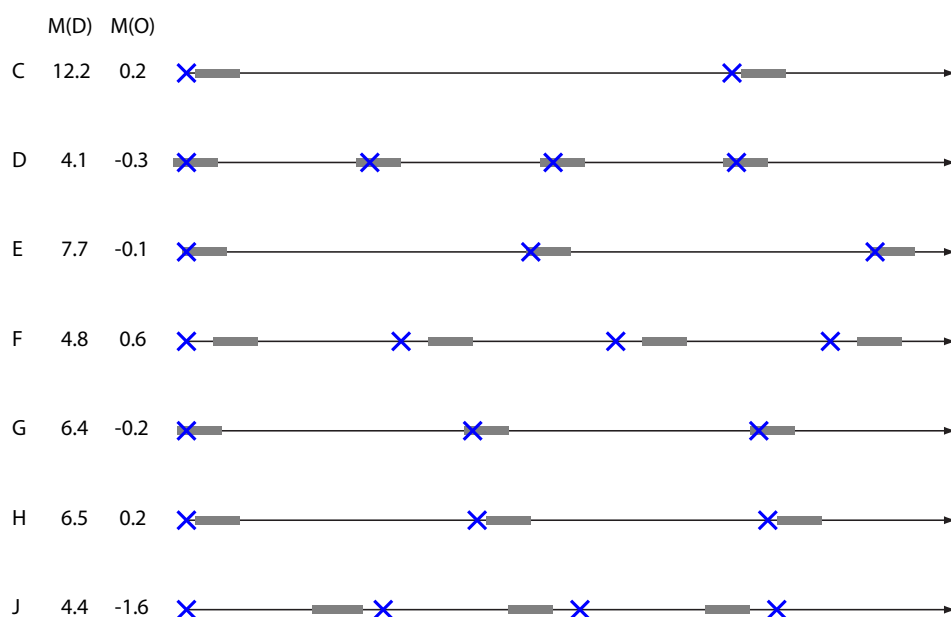


Figure 8.6: The estimated period when tactile motion instructions were perceived relative to passing the fall line. The crosses indicate the turning points on the rider's path (see Fig. 8.5 (a)), considering the average duration of turns as observed on footage ($M(D)$ in seconds, see Table 8.1 (c)). The rectangles show when the participants perceived the compound instructions (990 ms), considering the average time offset between passing the fall line and the system triggering instructions ($M(O)$ in seconds, see Table 8.1 (b)).

this sketch indicates that the instructions were triggered at slightly different times. The main reason could be that the participants' riding skills differed. On average, the instructions were most delayed for participant *F*, who perceived them after passing the fall line. This could indicate that he performed skidded turns and that the system detected the riding edge when he exerted more pressure on this edge while traversing the slope. Since *F*'s turns were short, these delayed instructions could have interfered with the movements that were required for returning to neutral position after pivoting the snowboard.

In contrast, participant *J* perceived the instructions before passing the fall line, which indicates that he carved the turns at high speed (see Fig. 8.5 (b)). The instructions did not interfere with his previous movements for returning to neutral position as he had already introduced the new turn. For the other participants, the slightly delayed instructions might not have interfered with these movements either. Since the compound instructions lasted one second, the participants had enough time to return to neutral position while traversing the slope before introducing the next turn.

In general, the instructions were less likely to interfere with the movements that were required for returning to neutral position.

Table 8.2: The course instructor’s rating of the participants’ skills in riding switch before and after the course. The scale ranged from very bad (1) to very good (10). Some volunteers had previously tried to ride switch or had attended courses to improve their skills.

| Participant | A | B | C | D | E | F | G | H | I | J |
|----------------------|-----|-----|----|-----|-----|-----|----|----|----|-----|
| Rating before course | 4 | 7 | 2 | 6 | 2 | 2 | 3 | 2 | 2 | 5 |
| Rating after course | 6 | 8 | 4 | 7 | 4 | 5 | 6 | 4 | 5 | 7 |
| Tried switch before | yes | yes | no | yes | yes | yes | no | no | no | yes |
| Prior course | yes | yes | no | yes | no | no | no | no | no | no |

Table 8.3: Number of falls during descents without tactile instructions (normal font) and with tactile instructions (bold font). Instructions were applied either during lessons in the morning (m) or in the afternoon (a).

| Participant | A | B | C | D | E | F | G | H | I | J |
|-------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Tactile instructions | m | a | m | a | m | a | m | a | m | a |
| First descent (before course) | - | - | 3 | 0 | 0 | 2 | 0 | 0 | 4 | 1 |
| All descents in the morning | 0 | 0 | 1 | 0 | 0 | 2 | 3 | 5 | 4 | 1 |
| All descents in the afternoon | 0 | 2 | 2 | 1 | 0 | 0 | 4 | 2 | 1 | 1 |
| Last descent (after course) | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |

8.4.2 The Participants’ Riding Skills (Video Analysis)

All participants’ improved their riding skills.

The participants did not receive spoken nor tactile instructions for the first and last descent. Table 8.2 summarizes the course instructor’s rating of these rides and the participants’ pre-experience. On average, they received a rating of $Mdn = 2.5$ ($Q1 = 2, Q3 = 4.75$) before the course and a rating of $Mdn = 5.5$ ($Q1 = 4.25, Q3 = 6.75$) after the course. The six volunteers *C, E, F, G, H* and *I* had little or no experience in riding switch.

Another instructor assessed the participants’ performance.

The course instructor was not available to analyze the footage. We have consulted another instructor from the SNOW SPORT Team, who agreed to review the footage and to assess the participants’ skills and progress. Uninformed that half of the descents included tactile instructions, he counted the number of mistakes and falls, and rated the overall quality of the descents, regarding the weight distribution and the upper body posture while also considering how dynamic, fluent, and safe these runs were.

Riding Mistakes

The participants fell less often after the course than before the course.

The number of falls is a simple metric that shows a snowboarder’s progress (see Table 8.3). On average, the participants fell more often during the first ride before the course ($M = 1.25, SD = 1.58$) than during the last ride after the course ($M = .25, SD = .46$). The number of falls during lessons in the morning ($M = 1.6, SD = .1.84$) was similar to the number of falls during lessons in the afternoon ($M = 1.3, SD = 1.25$). Also, the number of falls for riding without tactile instructions ($M = 1.5, SD = 1.78$) was similar to the

number of falls for riding with tactile instructions ($M = 1.4, SD = 1.35$).

The number of falls was not normally distributed (Shapiro-Wilk test). A Wilcoxon signed-rank test revealed that they were not significantly lower after the course ($Mdn = 0$) than before the course ($Mdn = .05$), $T = 1.5, n = 5, p = .10, r = -.1$; neither during lessons in the afternoon ($Mdn = 1$) than during lessons in the morning ($Mdn = 1$), $T = 10.5, n = 7, p = 0.55, r = -.03$; neither for riding with tactile instructions ($Mdn = 1$) than for riding without them ($Mdn = 1$), $T = 13, n = 7, p = .86, r = -.01$.

Table 8.4 summarizes the percentage of riding mistakes while pivoting the board. On average, the participants counter-rotated their torso more often during the first ride before the course ($M = 54.39\%, SE = 12.74\%$) than during the last ride after the course ($M = 33.32\%, SE = 7.15\%$). This difference was not significant $t(7) = 1.49, p = .179$ but almost represented a large effect $r = .49$. The average percentage of incorrect weight distributions was higher during the first ride ($M = 51.60\%, SE = 9.21\%$) than during the last ride ($M = 21.54\%, SE = 5.84\%$). This difference was highly significant $t(7) = 3.75, p < .01$ and did represent a large effect $r = .82$.

The participants did significantly fewer mistakes after than before the course.

The average percentage of counter-rotations during lessons in the morning ($M = 34.14\%, SE = 5.46\%$) was higher than during lessons in the afternoon ($M = 29.23\%, SE = 3.78\%$). This difference was not significant $t(9) = .92, p = .38, r = .29$. The average percentage of counter-rotations for riding without tactile instructions ($M = 36.45\%, SE = 3.72\%$) was higher than for riding with tactile instructions ($M = 26.92\%, SE = 5.15\%$). This difference was significant $t(9) = 2.07, p = .034$ (one-tailed) and did represent a large effect $r = .57$.

Tactile instructions significantly reduced the number of counter-rotations.

The average percentage of incorrect weight distributions during lessons in the morning ($M = 27.37\%, SE = 4.35\%$) was similar to the percentage of mistakes during lessons in the afternoon ($M = 26.72\%, SE = 4.36\%$). This difference was not significant $t(9) = .17, p = .87, r = .05$. The average percentage of incorrect weight distributions for riding without tactile instructions ($M = 28.87\%, SE = 4.15\%$) was higher than for riding with tactile instructions ($M = 25.22\%, SE = 4.47\%$). This difference was not significant $t(9) = .94, p = .19$ (one-tailed) but did represent a medium effect $r = .30$.

Tactile instructions slightly reduced the number of incorrect weight distributions.

Quality of Descents

Poor descents did not occur except for the last ride of participant *G* during lessons in the afternoon. This unsafe ride with two falls, counter-rotation, and incorrect weight distribution received low ratings. Also, two descents were difficult to grade for participant *D* in the afternoon. He jumped while pivoting the board, apparently trying to alternate between flexed and stretched legs, but his overall posture was less clear to assess according to the required body movements and resulted in lower ratings.

A few descents were difficult to grade.

Table 8.4: Percentage of riding mistakes while pivoting the board without tactile instructions (normal font) and with tactile instructions (bold font). The overall quality of descents, considering upper body rotation and weight distribution, was rated on a scale from very bad (1) to very good (10). The maximum cumulative score for descents in the morning and in the afternoon is 40. Tactile instructions were applied either in the morning (m) or in the afternoon (a). No footage of participants *A* and *B* has been recorded for the first trial.

| | Participant | | | <i>A</i> | <i>B</i> | <i>C</i> | <i>D</i> | <i>E</i> | <i>F</i> | <i>G</i> | <i>H</i> | <i>I</i> | <i>J</i> |
|-------------------------------|-----------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|----------|----------|
| | m | a | | | | | | | | | | | |
| First descent (before course) | Tactile instructions | | | | | | | | | | | | |
| | Counter-rotation (%) | - | - | 100 | 42.9 | 33.3 | 100 | 16.7 | 11.1 | 85.7 | 45.5 | | |
| | Incorrect weight distribution (%) | - | - | 83.3 | 28.6 | 66.7 | 80.0 | 33.3 | 22.2 | 71.4 | 27.3 | | |
| | Rating of upper body rotation | - | - | 3 | 7 | 6 | 3 | 6 | 5 | 3 | 5 | | |
| All descents in the morning | Rating of weight distribution | - | - | 2 | 7 | 3 | 4 | 5 | 7 | 3 | 6 | | |
| | Counter-rotation (%) | 42.9 | 46.7 | 23.8 | 12.5 | 15.4 | 35.7 | 14.8 | 38.7 | 65.8 | 45.2 | | |
| | Incorrect weight distribution (%) | 28.6 | 0.0 | 52.4 | 25.0 | 26.9 | 28.6 | 18.5 | 29.0 | 42.1 | 22.6 | | |
| | Rating of upper body rotation | 26 | 28 | 28 | 33 | 24 | 27 | 30 | 25 | 26 | 24 | | |
| All descents in the afternoon | Rating of weight distribution | 24 | 31 | 27 | 27 | 19 | 23 | 28 | 29 | 23 | 29 | | |
| | Counter-rotation (%) | 40.7 | 25.0 | 20.0 | 10.7 | 43.5 | 26.9 | 33.3 | 18.9 | 48.1 | 25.0 | | |
| | Incorrect weight distribution (%) | 29.6 | 16.7 | 50.0 | 7.1 | 26.1 | 11.5 | 37.0 | 16.2 | 40.7 | 32.1 | | |
| | Rating of upper body rotation | 30 | 31 | 30 | 27 | 26 | 27 | 23 | 31 | 22 | 30 | | |
| Last descent (after course) | Rating of weight distribution | 32 | 29 | 20 | 25 | 23 | 28 | 24 | 32 | 25 | 33 | | |
| | Counter-rotation (%) | 20.0 | 14.3 | 40.0 | 42.9 | 25.0 | 14.3 | 25.0 | 11.1 | 33.3 | 75.0 | | |
| | Incorrect weight distribution (%) | 40.0 | 42.9 | 40.0 | 14.3 | 37.5 | 0.0 | 12.5 | 11.1 | 44.4 | 12.5 | | |
| | Rating of upper body rotation | 9 | 7 | 8 | 7 | 8 | 7 | 7 | 8 | 8 | 6 | | |
| Last descent (after course) | Rating of weight distribution | 8 | 6 | 7 | 6 | 6 | 8 | 7 | 8 | 6 | 7 | | |

Table 8.4 also summarizes the instructor's overall ratings of the quality of descents while also considering the posture of the upper and lower body. A Wilcoxon signed-rank test revealed that the participants received significantly lower scores for upper body rotation during the first ride before the course ($Mdn = 5$) than during the last ride after the course ($Mdn = 7.5$), $T = 0, n = 7, p = .02$, which did represent a large effect $r = -.59$. Also, the scores regarding the weight distribution was significantly lower during the first ride ($Mdn = 4.5$) than during the last ride ($Mdn = 7$), $T = 2, n = 8, p = .02$, which did represent a large effect $r = -.56$.

Overall riding skills were significantly better after the course than before the course

Regarding upper body rotation, the participants scored similarly during lessons in the morning ($Mdn = 26.5$) and in the afternoon ($Mdn = 28.5$), $T = 20.5, n = 9, p = .81, r = -.05$. Also, they scored similarly for riding without tactile instructions ($Mdn = 26.5$) and for riding with tactile instructions ($Mdn = 27.5$), $T = 14.5, n = 9, p = .34, r = -.21$.

Overall scores for upper body rotation were similar in both conditions.

Regarding weight distribution, the participants scored similarly during lessons in the morning ($Mdn = 27$) and during lessons in the afternoon ($Mdn = 26.5$), $T = 19, n = 10, p = .38, r = -.19$. Also, they scored similarly for riding without tactile instructions ($Mdn = 26$) and for riding with tactile instructions ($Mdn = 27.5$), $T = 22, n = 10, p = .57, r = -.13$.

Overall scores for weight distribution were similar in both conditions.

Individual Progress

The last descent at the end of the experiment showed that *C*, *E*, *F* and *I* most benefitted from the course. Inexperienced in riding switch, they noticeably reduced both mistakes during the last ride compared to the first ride (see Table 8.4). Three of them (*C*, *F*, *I*) also fell less often after the course than before the course (see Table 8.3). *D*, *G*, *H* and *J* improved their weight distribution, yet *G* and *J* made more upper body mistakes. Overall, the first-time snowboarder *H* performed best before the course and second best after the course. During the course, however, her performance was lower and included several falls. This was also the case with *G*.

The inexperienced participants most benefitted from the course.

A, *C*, *E*, *G* and *I* received tactile instructions in the morning. *E* and *G* were inexperienced in riding switch and most benefitted from these instructions. Their percentage of incorrect upper body posture (*E*, *G*) and incorrect weight distribution (*G*) was noticeably lower during descents in the morning than during descents without tactile instructions in the afternoon (see Table 8.4). For *G*, the overall quality of descents was better in the morning than in the afternoon, although the number of falls was similar (see Table 8.3). For *E*, the overall quality of descents was marginally better in the afternoon.

Two inexperienced participants benefitted from tactile motion instructions in the morning.

The performance of the other three participants (*A*, *C*, *I*) did not noticeably change in the afternoon after riding with tactile instructions in the morning (see Table 8.4). The percentage of mistakes remained similar for *A* (advanced rider), yet the overall quality of descents was better in the afternoon. For *C* (inexperienced rider), the percentage of mistakes was

Three participants showed a steady performance with tactile motion instructions in the morning and without them in the afternoon.

similar throughout the day, yet the overall quality of descents regarding weight distribution was lower in the afternoon. Participant *I* (inexperienced rider) rode more often with wrong upper body posture and fell more often in the morning than in the afternoon (4 falls vs. 1 fall, see Table 8.3), yet the percentage of incorrect weight distributions and the overall quality of descents remained similar throughout the day.

Two participants noticeably improved their skills in the afternoon when riding with tactile motion instructions.

B, D, F, H and *J* received tactile instructions in the afternoon. *D, F* and *H* did fewer mistakes during these rides (see Table 8.4). *F* and *H* fell less often than in the morning (see Table 8.3). The overall quality of descents slightly improved for *F* (weight distribution) and *H* (upper body posture) but slightly worsened for *D* (upper body posture). *B* and *J* did fewer upper body mistakes but rode slightly more often with improper weight distribution. *B* fell twice in the afternoon. Even so, the overall quality of descents remained similar for *B* throughout the course but improved for *J*.

8.4.3 The Participants' Opinion (Questionnaire Results)

Half of the group considered riding switch as difficult; all participants benefitted from the course. Tactile motion instructions were good to perceive.

Fig. 8.7 shows the participants' assessment of their skills. Half of the group (*B, F, H, I, J*) considered riding switch as difficult to learn, whereas the other five participants disagreed. Overall, all participants agreed to have much improved their riding technique during the course.

Fig. 8.8 summarizes the participants' view on tactile instructions for learning to ride switch. All agreed that they did not have difficulty in perceiving these instructions. Six participants stated that tactile and spoken instructions corresponded, whereas for *B, D, H* and *J* the tactile instructions somewhat represented the spoken instructions issued before the ride.

Five participants rated tactile instructions as helpful.

The participants disagreed when asked if these instructions helped them to ride switch with correct posture: *A, E, F, G* and *I* considered them as helpful; *B, C,* and *H* were undecided; *D* and *J* stated they did not help. In general, tactile instructions somewhat increased their motivation to ride with correct posture and somewhat improved the quality of their descents.

Tactile motion instructions did not distract during the ride.

Nine participants, except *B*, agreed that tactile instructions did not distract from carrying out spoken instructions issued before the ride. Even so, four participants (*B, E, H, J*) mentioned that it was difficult to pay attention to the tactile stimuli while carrying out spoken instructions.

All participants preferred descents with tactile motion instructions for learning new riding techniques.

Half of the group (*A, C, D, E, I*) considered tactile instructions important for learning new riding techniques (see Fig. 8.9). *B, F, G* and *H* regarded them as moderately important, whereas the skilled rider *J* ascribed little importance to them. Even so, they all stated to prefer lessons enhanced with tactile instructions ($Mdn = 5$) over lessons exclusively with spoken instructions issued before descents ($Mdn = 2$), $T = 0, n = 10, p < .01, r = -.64$ (Wilcoxon signed-rank test, see Fig. 8.9).

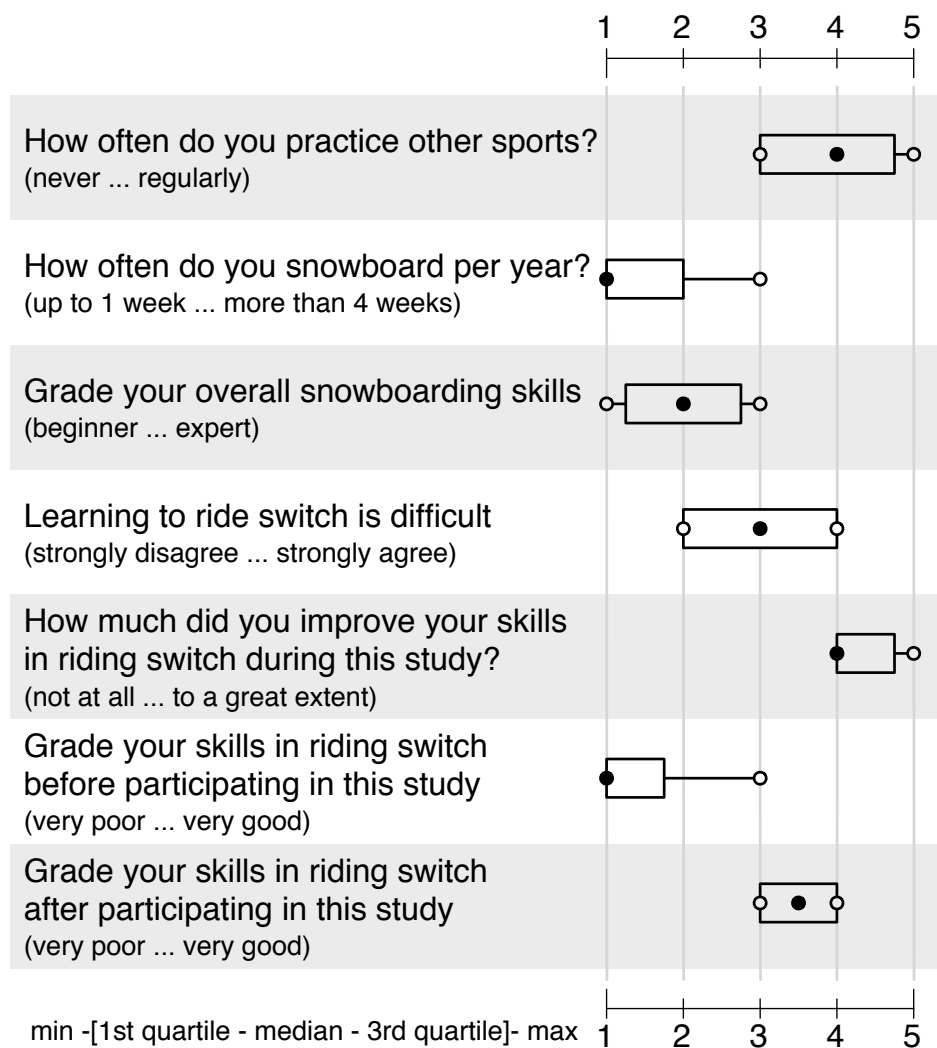


Figure 8.7: Likert scale ratings of the participants' snowboarding skills before and after participating in the snowboarding course.

The three beginners *E*, *H* and *I* preferred to receive instructions during all trials. The other participants, including both beginners and advanced riders, disagreed. They preferred to receive feedback only if their posture was incorrect (see Fig. 8.9).

Beginners preferred continual feedback.

The snowboard beginner *E* disliked the system to inadvertently trigger instructions when pausing on the slope. Ideally, the system should only provide feedback during the ride. Also, he mentioned that although the tactile instructions were a bit too much when practicing a new exercise, this feedback was helpful at later stages when repeating the learned movements. Participant *D* commented that the patterns for upper body rotation were not distinct enough. Participant *I* mentioned that he had received instructions at the shoulders towards the end of his turns.

Negative comments on tactile motion instructions

Nine participants explained what they liked about tactile instructions: "Direct feedback during the ride" (*A*); "Quite accurate" (*B*); "Clear enough to

Positive comments on tactile motion instructions

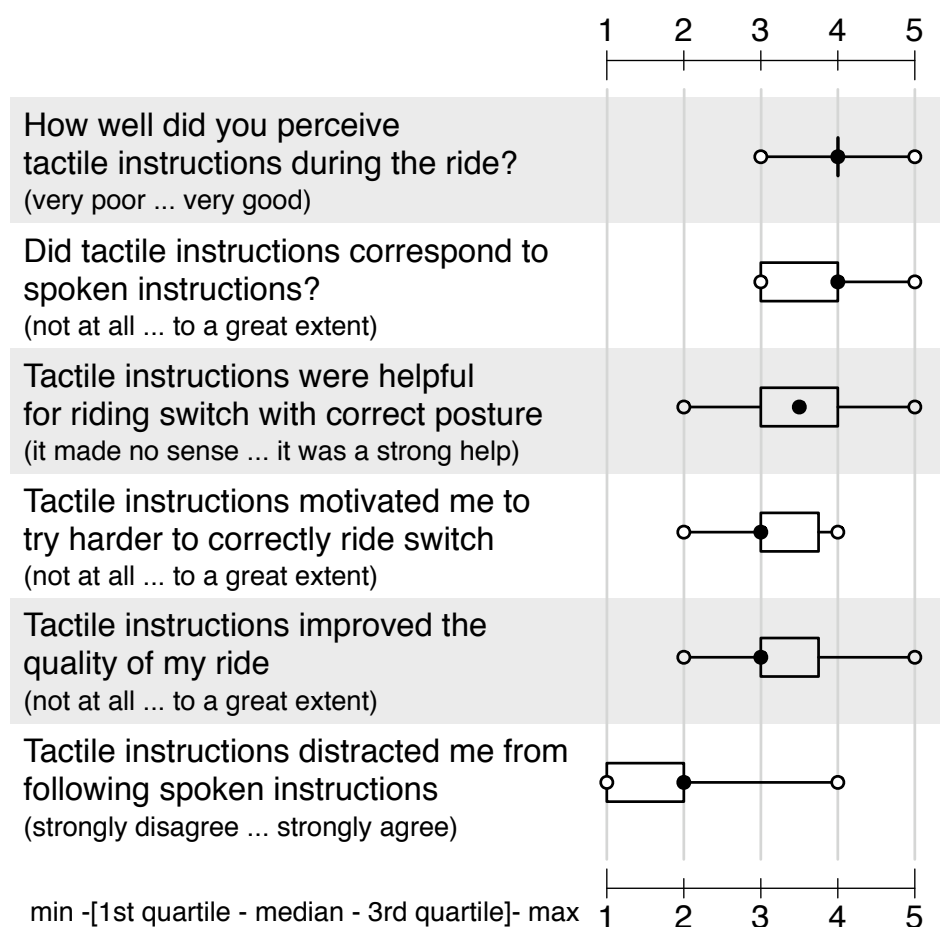


Figure 8.8: Likert scale ratings of tactile motion instructions that signaled correct posture while riding switch.

notice and locate, but not too strong to distract” (*C*); “Motors were comfortable to wear” (*J*); “Feedback at the thigh reminded of correct position and kept me thinking about the weight distribution” (*D*, *F*, *I*); “Feedback reminded of correct basic posture when advancing in the course” (*E*); “Feedback was an additional clue to *activate* involved body parts” (*H*).

Some participants only followed spoken instructions.

Five participants provided further comments on the wearable system and on tactile motion instructions. *A* was annoyed by the sensor cables inside the snowboard pants. *C* and *D* perceived tactile instructions but carried out spoken instructions issued before the ride. *D* concentrated on the speed and the movements during descents. Participant *I* concentrated on the tactile instruction that was applied either to the shoulder or to the thigh. Overall, he had great fun during the course and would also very much recommend this system to other snowboarders.

Some participants recommended tactile instructions for snowboarders who already had basic riding skills.

Participant *C* has never before tried to ride switch. Consequently, she concentrated on keeping her balance to avoid falls. Although she noticed feedback, she did not react to these instructions: “*Since riding switch was completely new to me, I was very concentrated on not falling (in the begin-*

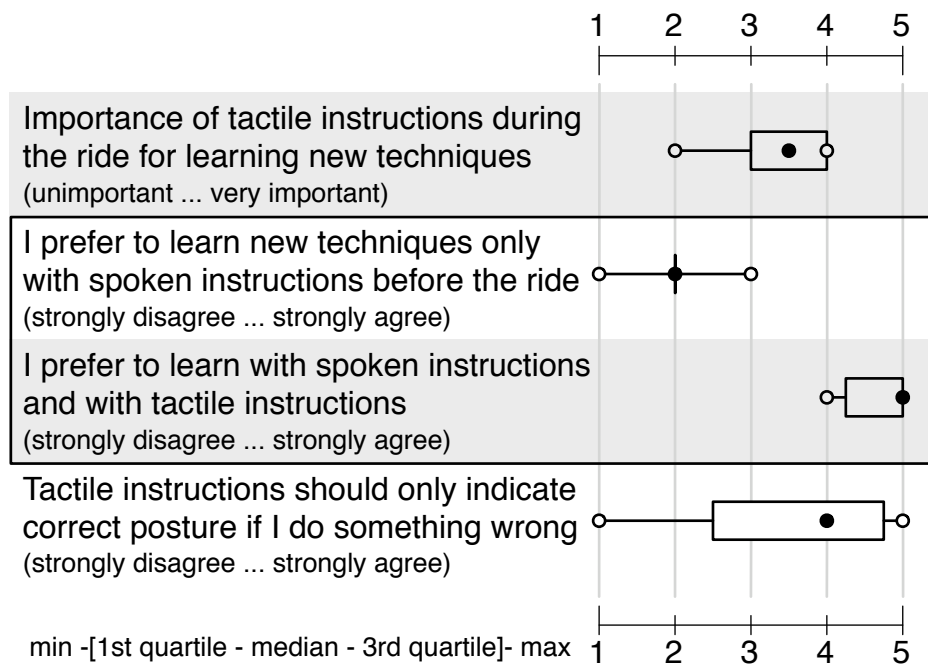


Figure 8.9: Likert scale ratings of the participants' opinion on using tactile motion instructions for learning new riding techniques. The participants clearly preferred to learn with tactile instructions (framed questions).

ning) and tried to follow spoken instructions. I did not really react to the tactile instructions, although I noticed them, because there were so many other things to think about. I guess it would have been easier for me to regard them as additional instructions after some time of practice, once the basic way of riding was familiar to me and when I could spend attention on more exact riding, e.g., at the end of the day.”. Participant J also mentioned that tactile instructions could help snowboarders to correct and maintain proper posture once they can ride better.

Table 8.5 summarizes the main results obtained from the questionnaires, including the participants' snowboarding skills and their overall opinion on tactile motion instructions.

8.5 Discussion

8.5.1 The Wearable System

Unlike to our previous field studies on the slope, the wearable system withstood more demanding situations during descents, including falls, a different layering of force sensors, reduced sampling rate, and simultaneous sensing and actuation. We did not experience problems with the sensors inside the boots, nor with the vibration motors. Nevertheless, one host device lost the Bluetooth connection to its SensAct box during one descent, crashed,

We experienced only minor problems with the wearable system.

Table 8.5: Summary of the participants' riding skills and their opinion on tactile motion instructions (see also Appendix D). This table contains the abbreviations beg. = beginner, adv. beg. = advanced beginner, adv. = advanced, undec. = undecided, and uk = unknown.

| Participant | A | B | C | D | E | F | G | H | I | J |
|---------------------------------|-----------|-----------|-----------|----------|-------|----------|-----------|----------|------|----------|
| Gender | male | male | female | male | male | male | male | female | male | male |
| Snowboards for ... years | 7 | 10 | 4 | 1.5 | 2 | 2 | 3 | 0 | 2 | 10 |
| Rated his/her overall skills | adv. beg. | adv. beg. | adv. beg. | adv. | beg. | adv. | adv. beg. | beg. | beg. | adv. |
| Participated prior course | yes | yes | no | yes | no | no | no | no | no | no |
| Tried switch before | yes | yes | no | yes | yes | yes | no | no | no | yes |
| Riding switch is difficult | no | yes | no | no | no | yes | no | yes | yes | yes |
| Tactile motion instructions: | | | | | | | | | | |
| In the morning/afternoon | m | a | m | a | m | a | m | a | m | a |
| Previously experienced | no | yes | yes | no | yes | no | no | no | no | no |
| Corresponded to spoken instr. | yes | somewhat | yes | somewhat | yes | yes | yes | somewhat | yes | somewhat |
| Were helpful for riding switch | yes | undec. | undec. | no | yes | yes | yes | undec. | yes | no |
| Distracted from spoken instr. | no | yes | no | no | no | no | no | no | no | no |
| Are important for learning | yes | moderate | yes | yes | yes | moderate | moderate | moderate | yes | no |
| Prefers only spoken instr. | no | no | no | no | no | no | undec. | no | no | undec. |
| Prefers spoken + tactile instr. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Only indicate mistakes | yes | yes | yes | yes | no | yes | yes | no | no | yes |
| Additional comments: | | | | | | | | | | |
| I followed tactile instructions | yes | | no | no | yes | yes | | yes | yes | |
| They remind of correct posture | | | | | | | | | | |
| Tactile + spoken is taxing | | yes | yes | | yes | | | yes | | yes |
| Proposed for advanced riders | | | (yes) | | (yes) | | | | | yes |
| Course instructor's rating: | | | | | | | | | | |
| Riding switch before the course | 4 | 7 | 2 | 6 | 2 | 2 | 3 | 2 | 2 | 5 |
| Riding switch after the course | 6 | 8 | 4 | 7 | 4 | 5 | 6 | 4 | 5 | 7 |
| Turns with instructions (%) | uk | uk | 100 | 87.0 | 100 | 100 | 51.6 | 100 | uk | 100 |
| Average delay (seconds) | uk | uk | 0.2 | -0.3 | -0.1 | 0.6 | -0.2 | 0.2 | uk | -1.6 |

and lost the corresponding sensor log file. Moreover, one participant wore a short jacket that did not protect the pouch from snow during falls; the SensAct box got wet, stopped to function, and had to be replaced.

Our wearable sensing system recognized fewer turns (90.97%) than we have expected (96.72%), considering the off-line evaluation of our algorithm for classifying the riding edge based on force sensor data recorded during descents (see section 4.4). There are several possible explanations for this. For this field study, we have placed the force sensors between the outer and inner boot to shield the rider from feeling sensor cables during descents. This new layering, however, made it more difficult to precisely position the sensors under the ball of each foot. In addition, the thick material of the inner boot might have dampened the sensor measurements. Another reason might have been that the participants did not descend with their preferred foot pointing forward, as was the case in our first field study. Since riding switch was unfamiliar to them, tensed muscles of the feet might have further influenced the force sensor measurements.

The wearable system missed 9% of turns.

All participants performed at least five turns from the top to the middle of the slope while riding with tactile motion instructions. Therefore, one descent likely included at least ten turns. On average, the participants experienced concurrent instructions during nine turns.

Nine of ten turns included tactile motion instructions.

The observed turning points on footage often lay between two frames, such as between the time stamps 14:04:49 and 14:04:50. Our participants sometimes quickly passed these points, whereas at other times they rode more slowly. Furthermore, the host devices logged time stamps at one-second resolution. Consequently, the duration of turns given in Table 8.1 and the estimated point in time when the participants perceived tactile motion instructions are approximate values.

Approximate values for the duration of turns

8.5.2 Video Analysis and Questionnaire Results

Unsurprisingly, all participants improved their skills in riding switch. In general, the more they practiced, the more correct and safer they descended. The difference between their riding skills during lessons in the morning and in the afternoon confirmed a gentle learning effect, which was most noticeable for upper body rotation. Moreover, their riding skills were significantly better after the course: the number of counter-rotations, wrong weight distributions, and falls were lower during the last descent than the first descent. Also, the instructor's rating after the course was higher than before the course, as were the participants' ratings of their own skills.

The course helped the participants to improve their riding skills.

We have previously reported that young adults who were asked to descend a slope without performing specific exercises were able to perceive well tactile motion instructions, although the less experienced snowboarders could not pay attention to identify the direction that these stimuli displayed on the skin (see section 6.3.2). The findings of this study confirmed that all par-

All participants perceived tactile motion instructions regardless of their riding skills.

participants, regardless of their riding skills, were able to perceive the applied instructions, although they faced demanding conditions during the course. These candidates practiced an unfamiliar riding technique. In addition, we have shortened the length of the tactile patterns to half a second. For these reasons, we can conclude that in activities that are physically and cognitively less demanding than snowboarding, young adults will be able to perceive the composed tactile motion instruction patterns.

Spoken instructions could interfere with tactile motion instructions.

The course instructor explained correct technique and issued exercises and instructions before each descent. These spoken instructions apparently influenced some participants. For example, the participants *C* and *D* stated that they only considered the spoken instructions. Although they did perceive the tactile instructions, they did not pay attention to these cues. Furthermore, three snowboard beginners (*C*, *E*, *H*) and two advanced riders (*B*, *J*) had some difficulty in paying attention to tactile instructions while carrying out spoken instructions. This explains in part why they did not consider tactile instructions helpful for riding switch. Had they not received spoken instructions before descending the slope, we surmise that they would have regarded these instructions differently.

Some inexperienced riders could attend to concurrent tactile instructions.

Five participants (*A*, *D*, *F*, *G*, *I*) did not mention difficulty in paying attention to the tactile motion instructions. Moreover, it seems that some of our inexperienced snowboarders benefitted from this concurrent feedback, whereas some advanced riders did not. These findings contradict the opinion of the interviewed instructors who stated that tactile feedback during descents might be useful only for advanced riders (see section 4.1).

Three beginners preferred to receive tactile motion instructions during all turns.

Three of the four participants who were less experienced in riding switch (*E*, *H*, *I*) preferred to receive instructions during all turns, whereas the more experienced riders favored feedback only for incorrect posture. This indicates that those who had to pay more attention how to move correctly benefitted from continual feedback. In fact, participant *E* rode better with tactile instructions in the morning than without them in the afternoon.

Two beginners rode better with tactile instructions.

Besides *E*, *G* also rode noticeably better with tactile motion instructions in the morning than without them in the afternoon. In general, practice runs in the morning should have reduced mistakes in the afternoon but these participants performed more mistakes. In addition, they confirmed that these instructions were helpful, although they did not consider riding switch as difficult. *E* considered the instructions as motivating and stated they improved the quality of his descents to a great extent. *G* considered them as somewhat motivating. Therefore, we can attribute *E*'s and *G*'s superior performance in the morning to tactile motion instructions.

Three participants apparently did not make progress during the course but valued tactile motion instructions in the morning.

The riding skills of the other three participants who received tactile motion instructions in the morning (*A*, *C*, *I*) remained substantially the same throughout the course. Participant *I*, however, fell less often and improved upper body posture in the afternoon, which indicates a learning effect due to previous practice runs. Even so, *A* and *I* stated that these instructions helped with riding switch. *C* was undecided if the instructions were helpful,

but she only carried out spoken instructions. She regarded tactile feedback as helpful after some time of practice, once she could pay attention to riding that was more exact.

All five participants who received tactile motion instructions in the afternoon improved their skills after the break: *D*, *F* and *H* did noticeably fewer mistakes; *B* and *J* improved upper body posture, although they rode more often with improper weight distribution. These participants could have improved their skills because of previous practice runs in the morning and because of concurrent instructions. Even so, the questionnaire indicates that only *F* benefitted from tactile motion instructions. Although he was inexperienced in riding switch, and although he received delayed instructions after passing the fall line (see Fig. 8.6), he did not feel distracted and stated that these instructions were helpful. The first-time snowboarder *H* did not feel distracted either. Nevertheless, she had difficulty in paying attention to these concurrent instructions while carrying out spoken instructions. This indicates that she mainly improved her skills because of her previous descents in the morning.

One inexperienced snowboarder benefitted from tactile motion instructions in the afternoon.

The participants *B*, *D* and *J*, who had some experience in riding switch, probably did not take advantage of tactile instructions in the afternoon. After the break, they also practiced exercises that were less appropriate for the chosen tactile instructions. These exercises certainly influenced their performance and opinion. Overall, their statements that tactile instructions somewhat corresponded to spoken instructions and that this feedback did not help with riding switch indicates that their previous practice runs in the morning mainly helped them to improve their skills in the afternoon.

The more demanding exercises in the afternoon were less suited for the chosen tactile instructions.

Even so, we can reject the null hypothesis that tactile motion instructions do not reduce riding mistakes in snowboarding compared to descending without these instructions. On average, these instructions significantly reduced the number of counter-rotations and reduced the number of incorrect weight distributions (see section 8.4.2). This indicates that concurrent tactile motion instructions did improve the performance in riding switch. Overall, the results of our study support the findings of sport scientists who have shown that concurrent feedback on performance could improve performance and learning of motor skills [Shea and Wulf, 1999, Wulf, 2007].

We can reject the null hypothesis.

In summary, nine of ten participants considered tactile motion instructions as important or as moderately important for learning new riding techniques in snowboarding. Even so, their view on these concurrent instructions as experienced in this experiment varied. Five participants (*A*, *E*, *F*, *G*, *I*), four inexperienced and one slightly advanced in riding switch, mentioned that the instructions helped them to improve their skills. The instructions were less helpful for the other five participants (*B*, *C*, *D*, *H*, *J*): three advanced riders also practiced exercises that were less suited for the chosen instructions; two inexperienced and three advanced riders had difficulty in paying attention to these instructions, in particular when carrying out spoken instructions.

All except one participant saw a benefit in tactile instructions.

8.5.3 Study Limitations

Our findings indicate that providing tactile motion instructions during descents could support snowboarders in learning an unfamiliar riding technique. This study, however, had some limitations that should be considered.

The participants' skills varied.

People have different learning abilities. While some quickly learn new motion sequences, others need long practice. We were not able to recruit only volunteers with similar pre-experience in snowboarding and in riding switch. Consequently, our participants' performance varied and likely influenced their opinion if tactile motion instructions were helpful. Even so, we have received valuable insights from a broader user base.

Confounding factors

Our participants' performance also depended on factors that we were not able to control. For example, they descended at different speed, they chose different riding paths, and the slope was open to other winter sport practitioners who crossed and influenced our participants' riding paths. Moreover, fatigue after several descents is common in snowboarding and could have degraded their performance in the afternoon.

This short-term study had few participants.

In general, snowboarding requires lots of practice. This field study lasted one day and comprised eight descents with about ten turns per trial. Four descents included tactile instructions. Although all participants could improve their technique during the course, four descents on a slope of 520 meters (1700 ft) length might not provide representative data on learning success, in particular because our user group was small. Also, due to time constraints for conducting this study, the instructor assessed the participants' acquired skills in riding switch immediately after the course, which did not reveal long-term learning effects.

Studies on motor learning measure performance and learning over several days.

Studies on motor skill learning typically involve a between-subjects design with one group for each experimental condition. To account for the variability in performance, as many as thirty participants per group perform several trials on two consecutive days. Moreover, a retention test measures long-term learning effects on the third day or later.

Tactile motion instructions conveyed information that was not available in the control condition.

Another issue is that tactile motion instructions provided additional information how to move the body. This information was not available in the control condition and could be one reason why descending with tactile motion instructions reduced the average number of riding mistakes. Future studies should compare, for example, concurrent tactile motion instructions to concurrent spoken instructions. This approach would ensure that the participants receive the same amount of feedback during all trials.

The participants also experienced tactile motion instructions during turns with correct posture.

Other limitations concern our wearable sensing and feedback system. This system could not detect riding mistakes. For this reason, we have programmed the host device to automatically issue tactile motion instructions during all turns such that our participants also experienced concurrent instructions when their posture was correct. Consequently, we cannot gen-

eralize the reported findings to situations when athletes will only receive feedback or instructions on incorrect posture and body movements.

Moreover, our participants did not receive tactile motion instructions at the very moment when they had to execute the body movements while introducing a turn and while pivoting the snowboard. Instead, they received instructions after introducing a turn, as soon as the system detected that the board has been pivoted to the other edge. In fact, participant *J* received instructions after passing the fall line, and participant *I* stated that he perceived feedback at the shoulders towards the end his turns. Our course instructor who initially tested the system also mentioned that some instructions were delayed. Since these delayed instructions did not match to the movements that were required in the current riding situation, our participants were less likely to execute these instructions, which could have influenced their performance and opinion.

Tactile motion instructions were slightly delayed.

All participants experienced tactile motion instructions for the first time. The unfamiliar wearable technology with artificial tactile stimuli probably influenced their opinion as well. Moreover, they knew that we observed and videotaped their descents (Hawthorne effect) [Landsberger, 1968]. Therefore, it is possible that those snowboarders who rode better with tactile instructions than without them intentionally paid more attention to correct their posture. Also, even those participants who mentioned that these instructions were not helpful for riding switch stated to prefer lessons augmented with tactile instructions to traditional lessons. A long-term study might help to avoid such unfavorable experimental effects, in particular once the participants become accustomed to the new technology.

The novelty of the system likely influenced the performance in snowboarding and the participants' opinion.

It is easy to observe how feedback influences the accuracy of basketball shots, soccer passes, tennis strokes, or volleyball serves—the ball either hits or misses the target area. In snowboarding, however, it is often difficult to accurately assess a rider's posture from a distance because some movements remain concealed, even on footage. Also, coaches could have slightly different views on what constitutes correct riding technique. Unless snowboarders noticeably counter-rotate their torso or ride with too much weight towards the back foot, the threshold between incorrect and correct posture is debatable. For these reasons, our results were partially biased towards the viewpoint of the instructor who analyzed the footage. For example, the percentage of riding mistakes did not always seem to correspond to the overall ratings of the descents where the instructor also considered how safe and dynamic the participants descended the slope.

The instructors' ratings were biased.

Our findings require further investigation, considering other physical activities and motor skills that can be measured objectively. Nevertheless, we can state that tactile motion instructions could support athletes in improving their performance and in learning motor skills if the athletes have free cognitive resources to pay attention to these artificial tactile stimuli.

Further studies are required.

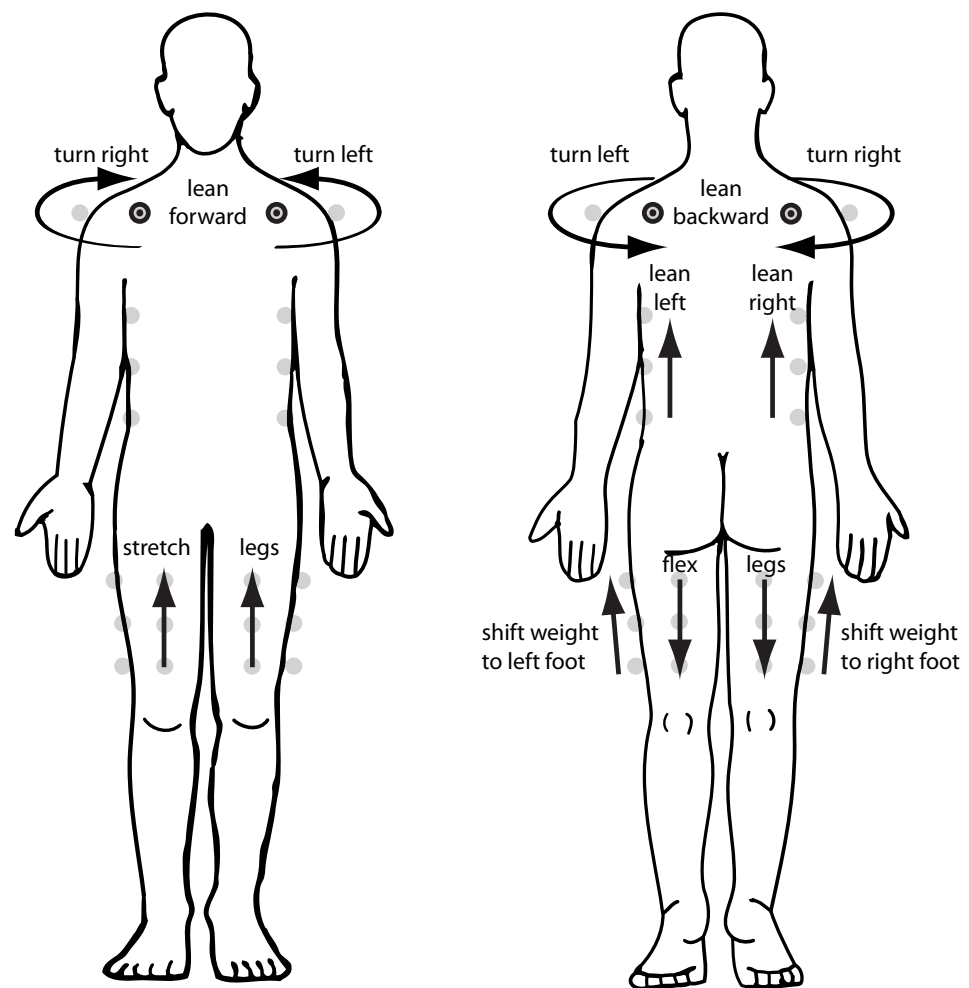


Figure 8.10: The final set of tactile motion instructions, based on stimuli that could be described to pull the body in the direction in which to perform the movements. The double-circles at the chest and back represent the localized sensations for the instructions *lean forward* (*backward*).

8.6 A General Set of Tactile Motion Instructions

Ten general instructions how to move the body

In this thesis, we have iteratively designed and evaluated artificial tactile stimuli that could serve as instructions how to move the body during physical activities. These stimuli comprised localized pulses and directional lines that young adults could intuitively associate with body movements when they perceived the evoked tactile sensations across the body for the first time. Based on the sensations that were most often associated with specific body movements, and considering the sensations that could be perceived and differentiated in active situation, we have composed ten tactile patterns as a general set of tactile motion instructions.

Instructions based on the pull metaphor

Fig. 8.10 illustrates these patterns and their possible meaning. In this sketch, the mapping between the evoked sensations and their meaning is based on the pull metaphor, which would prompt to move the body towards

the vibration. The formal notation of these patterns is (see Fig. 6.3 for the acronyms on body location and Table 6.4 for the acronyms on body movements):

Stretch the legs, flex the legs:

- $SL = R_U(TRV) + R_U(TLV)$ at the front of the thighs
- $FL = R_D(TRD) + R_D(TLD)$ at the back of the thighs

Shift the weight to the left / right foot:

- $WL = R_U(TLL)$ laterally at the left thigh
- $WR = R_U(TRL)$ laterally at the right thigh

Lean upper body to the left / right:

- $LL = R_U(BLL)$ laterally at the left side of the torso
- $LR = R_U(BRL)$ laterally at the right side of the torso

Lean upper body forward / backward:

- $LF = P^3(SLV) + P^3(SRV)$ at the upper chest
- $LB = P^3(SLD) + P^3(SRD)$ at the upper back

Turn upper body to the left / right:

- $TL = P^3(SLV) \rightarrow P^3(SLL) \rightarrow P^3(SLD)$ around the left shoulder
- $TR = P^3(SRV) \rightarrow P^3(SRL) \rightarrow P^3(SRD)$ around the right shoulder

Fig. 8.11 illustrates these patterns and their possible meaning considering the push metaphor. The mapping between the evoked sensations and their meaning would prompt to move the body away from the vibration. The patterns for the instructions to flex and to stretch the legs are the same as in Fig. 8.10, as several of our study participants recommended this mapping. The formal notation of these patterns is (see Fig. 6.3 for the acronyms on body location and Table 6.4 for the acronyms on body movements):

Instructions based
on the push
metaphor

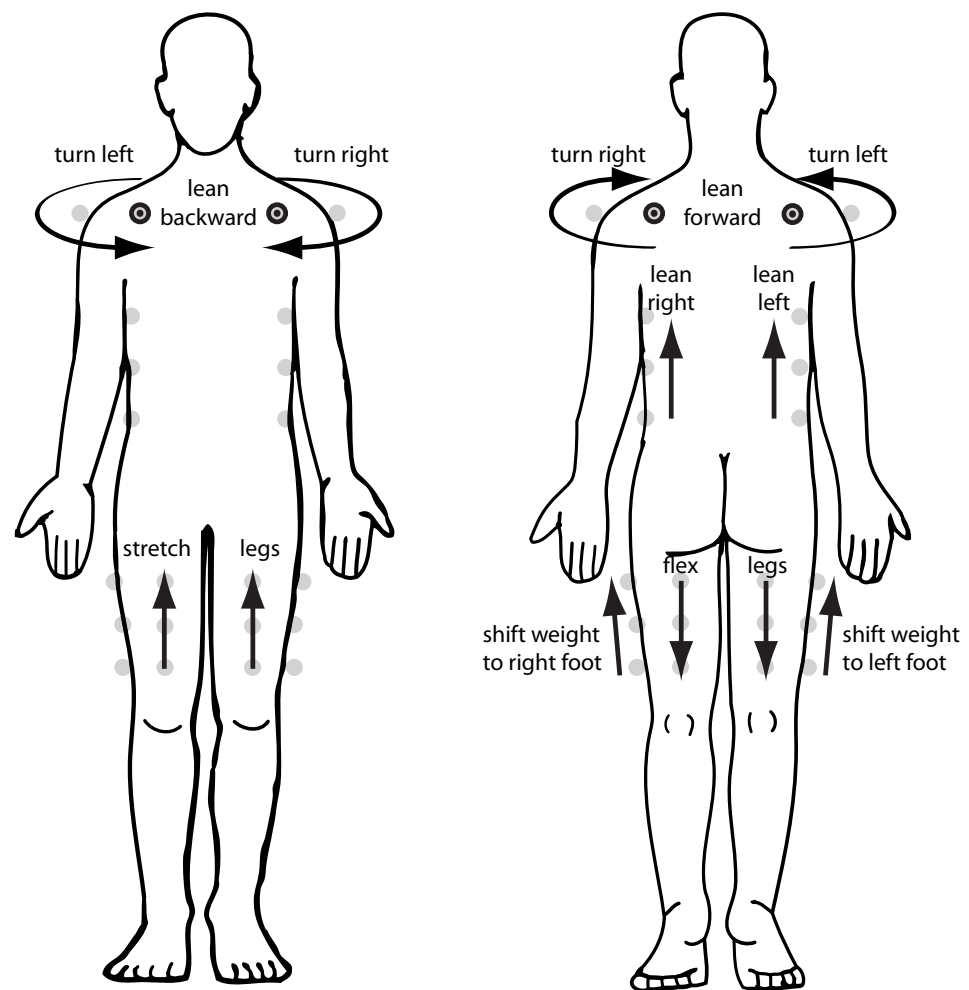


Figure 8.11: The final set of tactile motion instructions, based on stimuli that could be described to push the body in the direction in which to perform the movements. The double-circles at the chest and back represent the localized sensations for the instructions *lean forward* (*backward*).

Stretch the legs, flex the legs:

- $SL = R_U(TRV) + R_U(TLV)$ at the front of the thighs
- $FL = R_D(TRD) + R_D(TLD)$ at the back of the thighs

Shift the weight to the left / right foot:

- $WL = R_U(TRL)$ laterally at the right thigh
- $WR = R_U(TLL)$ laterally at the left thigh

Lean upper body to the left / right:

- $LL = R_U(BRL)$ laterally at the right side of the torso
- $LR = R_U(BLL)$ laterally at the left side of the torso

Lean upper body forward / backward:

- $LF = P^3(SLD) + P^3(SRD)$ at the upper back
- $LB = P^3(SLV) + P^3(SRV)$ at the upper chest

Turn upper body to the left / right:

- $TL = P^3(SRD) \rightarrow P^3(SRL) \rightarrow P^3(SRV)$ around the right shoulder
- $TR = P^3(SLD) \rightarrow P^3(SLL) \rightarrow P^3(SLV)$ around the left shoulder

In section 6.1, we have argued that tactile motion instructions should resemble real-world sensations; they should be expressive; and they should demand low conscious attention such that users could perceive and recognize these artificial tactile stimuli in active situations. Some of the composed tactile patterns fulfilled these requirements, whereas other patterns fulfilled them in part. We will now review these requirements.

Overall, our findings indicate that the amount of cognitive load that these tactile patterns imposed on the user was low. All ten patterns were perceived in active situations that were physically and cognitively demanding, for example while snowboarding, while riding a horse, and while balancing on the Wii fit balance board. Moreover, the messages that these unique patterns conveyed could be identified by the location where the tactile stimuli were applied to the body. A few patterns were misinterpreted, yet our findings indicate that the experimental conditions mainly caused these mistakes and not the characteristics of these patterns or the chosen mappings.

Directional lines evoked expressive sensations that intensified the sensory experience and that provided additional information how to move the body: the semicircular lines delivered around the shoulders (TL, TR); the lines delivered in downward direction to the back of the thighs (FL) and in upward direction to the front of the thighs (SL); and the lines delivered in upward direction laterally to the thighs (WL, WR) and laterally to the torso (LL, LR). While the patterns for TL, TR, FL and SL could be described to signal the direction in which to perform a movement, the patterns for WL, WR, LL, and LR could be described to represent the increased bending radius of the body when leaning sideways. Alternatively, considering the pull metaphor, directional lines in downward direction delivered laterally to the torso and laterally to the thighs (WL, WR, LL, LR) could be described to pull the body downward when leaning sideways (see Fig. 6.19).

In retrospect: the initial design requirements

Users do not have to spend much conscious attention to perceive and interpret the instructions.

Directional lines create expressive sensations that indicate how to move the body.

Tactile motion instructions resemble real-world pushing and pulling sensations.

Six patterns evoked sensations that were intuitively regarded to push the body or to pull the body (WL, WR, LL, LR, LF, LB). This characteristic of the artificially created tactile stimuli was advantageous because the evoked sensations resembled real-world pushing and pulling sensations. Also, FL stimulated the area close to the hollow of the knees where tactile sensations could naturally prompt to flex the legs, as if they were knee-jerk reactions.

Intuitive instructions

All ten patterns were applied to those body locations that were primarily involved in performing the intended movements. When perceived for the first time, on average five of these patterns were associated with these movements or were partially included in these movements. For this reason, the meaning that we have assigned to these patterns did not require much learning. The meaning of the other five patterns, however, was less obvious when they were perceived for the first time. The meaning of these patterns had to be learned. Even so, we found that all instructions could be quickly learned and recalled after an extended time.

Based on our participants' responses upon perceiving the designed tactile patterns for the first time, we can rank how intuitive the instructions were regarded to represent body movements (in descending order):

1. Shift the weight to the left foot or to the right foot (WL, WR)
2. Lean left or right; turn left or right (LL, LR, TL, TR)
3. Lean forward or backward; flex the legs (LF, LB, FL)
4. Stretch the legs (SL)

The meaning that tactile motion instructions convey should consider the movements that are required during the physical activity.

This ranking is based on the viewpoint of a few young adults and might vary for other users and age cohorts. Obviously, there is room for improving the designed instructions. In particular, *SL* was perceived as being less obvious, and the representation of this body movement as a tactile pattern seems to be more abstract than for the other body movements. Even so, the mapping that we have chosen between the composed patterns and their meaning is not fixed. The meaning of the patterns should consider the posture and the body movements that have to be performed during the intended physical activity, as this activity can influence how intuitive the instructions are regarded and how well they can be learned and recalled. For example, we have found that for horseback riding, the directional lines that were applied laterally to the thighs (*WL, WR*) would have been more appropriate to represent *Press the thighs together* for increasing the contact to the horse than *Shift the weight to the left (right)* (see section 6.3.3).

We represent tactile motion instructions by a larger footprint in the design space of mobile tactile interfaces.

Based on the findings on the perception and interpretation of the composed tactile patterns in active situations, we can reconsider the design space of mobile tactile interfaces. For some users, the chosen mapping between these patterns and their meaning might be less obvious. Also, the users' abilities in paying attention to these stimuli might vary depending on how demanding the physical activity is. For example, novices who learn new

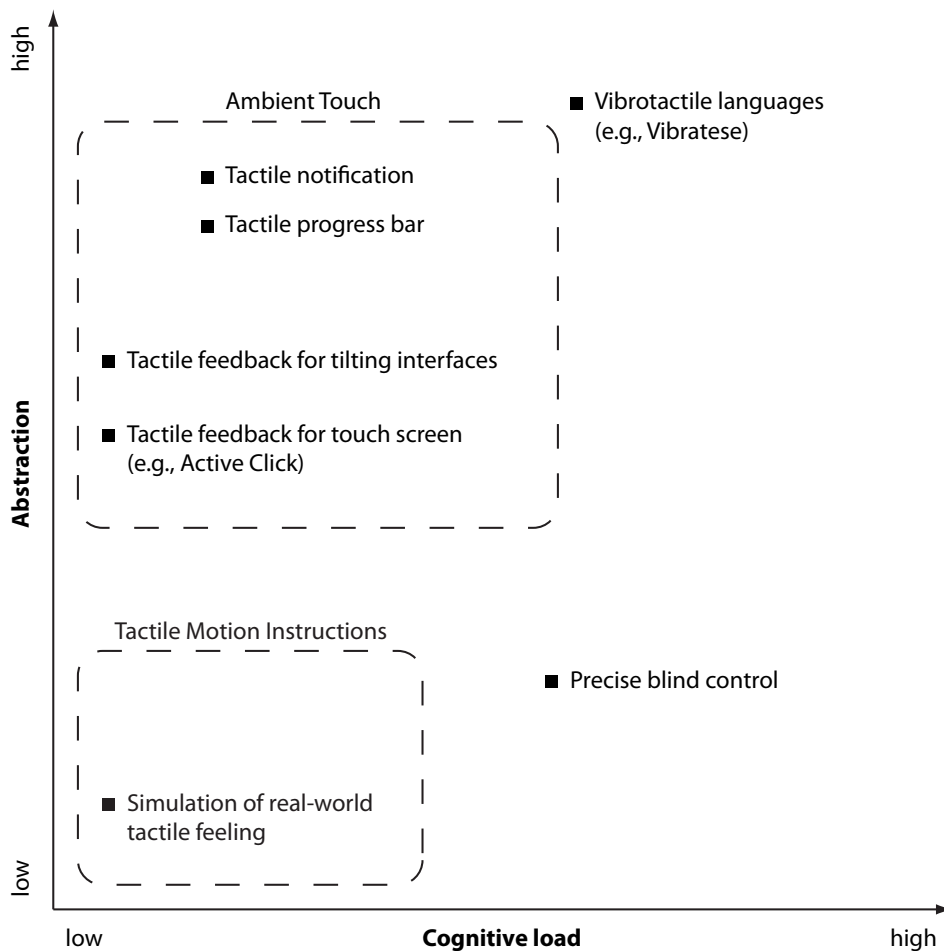


Figure 8.12: Some of the composed tactile motion instructions resemble real-world tactile sensations, whereas others are more abstract. Our set of instructions is best characterized by a larger footprint inside the design space. The users' intuitive interpretation of the tactile patterns and their abilities in perceiving these stimuli in active situation could vary (design space of mobile tactile interfaces adapted from [Poupyrev et al., 2002]).

sports could have difficulty to perceive these stimuli when they concentrate on various aspects of the sports' techniques and on keeping balance while moving the body. For these reasons, we have represented the introduced set of tactile motion instructions by a larger footprint in the design space (see Fig. 8.12). The size of this footprint considers how intuitive a user might regard the artificial tactile stimuli to represent body movements and how much attention a user might have to spend in order to perceive and to recall the meaning that has been assigned to these stimuli.

Table 8.6: Preference to being pushed or pulled (in percent), based on the intuitive responses of 29 participants.

| Stimulus location | Pull | Push |
|----------------------------|------|------|
| Upper chest | 62.1 | 37.9 |
| Upper back | 55.2 | 44.8 |
| Lateral side of the torso | 44.8 | 55.2 |
| Lateral side of the thighs | 48.3 | 51.7 |

8.7 Design Recommendations for Tactile Motion Instructions

The main findings from our empirical studies are summarized below, considering user comments and insights into the perception and interpretation of localized pulses and of directional lines that have been applied across the body in stationary and in active situations.

The same tactile stimulus can represent several body movements in an intuitive way.

In general, a tactile stimulus that was perceived at a specific body area prompted to move the same body area or neighboring areas or limbs. The range of reactions varied. Some reactions were concrete, whereas other reactions were vague. This indicates that a tactile stimulus that is applied to a specific body location can represent several body movements in an intuitive way. Even so, some people will have to learn the chosen mapping between the stimulus and its meaning because their intuitive reaction might differ when they perceive this stimulus for the first time.

Directional lines create expressive sensations that can indicate how to move the body.

Directional lines drawn on the body can intensify the sensory experience and can create expressive sensations that can indicate in which direction to perform a movement. Our participants preferred these lines, and they provided more responses and more concrete responses than to localized pulses. Even so, the direction of movement on the skin can be difficult to identify in active situations, in particular when the cognitive workload that the physical activity imposes on the user is high. For this reason, directional lines should not be used as primary encoding parameter for the meaning of an instruction. Instead, directional lines should be used as secondary parameter to redundantly encode the message.

A tactile stimulus can represent a push or a pull of the body.

Certain tactile stimuli can prompt to move towards or away from the vibration, as if the body was pulled or pushed: stimuli applied to the chest, to the back, laterally to the torso, and laterally to the thighs. These stimuli can be used as instructions that are based on the push or the pull metaphor, thereby signaling the direction in which to move the body. The mapping assigned to these stimuli—push or pull—can be quickly learned and recalled after an extended time, even if the user might intuitively move in the opposite direction upon perceiving these stimuli for the first time. Table 8.6 shows the preference to moving towards or away from these stimuli, based on the answers from 29 participants (see section 7.2 and section 7.3). Overall, we can see an almost equal proportion to both reactions, indepen-

dent of the location where the stimuli were applied. At the chest, however, tactile stimuli most often prompted to move towards the vibration.

The duration of localized pulses was 400 ms, which comprised three sequential pulses of $BD = 100$ ms bursts with $IBI = 50$ ms pauses. The duration of directional lines was 1300 ms, which stimulated three neighboring locations in line, each with three localized pulses (see Fig. 6.2). Both patterns were perceived in active situations. Moreover, these durations are short such that the user can quickly execute the required body movements. Even so, for compound instructions based on directional lines, which would sequentially apply two or more messages, the total duration of these patterns could be too long when quick reactions are required.

The duration of compound instructions might be too long.

Based on our observations and the findings of our studies, we found that the burst duration, the pauses, and the number of bursts could be reduced further without degrading the perception of the stimuli. In particular, reducing the number of stimulation points from three to two, and using two sequential pulses with a burst duration of $BD = 80$ ms did not impair the perception of the stimuli (see Fig. 8.4). Even so, for tactile motion instructions to be well perceivable and discriminable in active situations, the minimum duration of a pulse and the minimum number of pulses that might be required could vary depending on the physical activity and on the user's cognitive ability to pay attention to artificial tactile stimuli. Therefore, these minimum values require further investigation.

Directional lines can be shortened without impairing their perception.

We can state four guidelines for designing tactile motion instructions:

Recommendations for designing tactile motion instructions

- Body location should be used as primary parameter for encoding the meaning of tactile motion instruction patterns. This requires applying all patterns to unique body locations, which would allow users to differentiate between these patterns without paying attention to other characteristics of the tactile stimuli.
- The mapping between a stimulus and its meaning can represent a push or a pull of the body, thereby signaling the direction in which to perform the movement. For large instruction sets, a consistent metaphor should be applied in order to decrease the likelihood of misinterpreting the instructions.
- Directional lines can create expressive sensations that can indicate the direction in which to perform a movement. In a static situation, the direction of the sensation can be well perceived. Even so, in active situations, the direction could be difficult to identify. For this reason, directional lines should not be used as primary encoding parameter. They should be used as secondary parameter to redundantly encode the message and to intensify the sensation.
- While 100 ms is recommended as the minimum duration for a tactile message in a stationary situation (see section 5.3), for active situations we recommend two to three sequential pulses around 100 ms and

pauses around 50 ms. If these stimuli are applied to opposing body sites, they can be well perceived and localized.

8.8 Closing Remarks

The first field study on motor skill learning with tactile motion instructions

In this chapter, we have presented the first field study that investigated if tactile motion instructions could support athletes in learning motor skills. During a one-day snowboarding course, ten snowboarders practiced an unfamiliar riding technique. They experienced and compared traditional lessons, where the snowboard instructor provided spoken instructions before and feedback on performance after descents, with lessons where a wearable system additionally provided tactile motion instructions while descending the slope. These artificial tactile stimuli instructed the athletes how to move the body during turns.

Tactile instructions reduced mistakes during descents.

Our findings indicate that tactile motion instructions applied during descents could help snowboarders to correct their posture and to avoid two typical snowboarding mistakes. Moreover, the majority of our participants considered these instructions useful for learning. Even so, the benefits that they could provide during training also depend on the learner's cognitive ability to pay attention to these artificial tactile stimuli. While some people can focus their attention on concurrent tactile instructions during exercises, others might have difficulty in processing this additional sensory information, in particular when also carrying out spoken instructions.

This work contributed to research in motor learning.

Research in motor learning indicates that instructions and feedback on performance that are provided while executing body movements could improve the skills of athletes. Our findings support this claim and demonstrate that the tactile sense could be an alternative channel for conveying concurrent feedback and instructions, apart from the auditory and the visual channel. In particular, our work indicates that concurrent tactile instructions could support athletes in learning open skills under real-world conditions.

Premiere of a wearable snowboard training system

In addition, we have successfully demonstrated the first wearable assistant for snowboard training. This system used force sensors inside the boots to sense the weight distribution and to recognize the movements of the snowboard. Based on this context information, the system automatically triggered tactile motion instructions that guided the snowboarder to the correct posture and to the correct body movements during turns.

Recommendations for designing for tactile motion instructions

Finally, we have presented a set of recommendations for designing tactile motion instruction patterns, and we have presented a set of patterns that could be applied as instructions how to move the body during physical activities. These recommendations and the tactile patterns based on the findings on the perception and interpretation of artificial tactile stimuli that were iteratively evaluated with young adults in stationary and in active situations, considering laboratory conditions and real-world conditions.

Part III

Conclusion

Chapter 9

Conclusions

“I have not failed. I’ve just found 10,000 ways that won’t work.”

—*Thomas A. Edison*

In sports training, feedback on wrong posture and body movements is essential for learning motor skills. Even so, coaches often cannot provide feedback in time because they are spatially separated from athletes. To address this issue, we envisioned a wearable system that sensed and analyzed posture and body movements, and that automatically provided instructions how to correct wrong posture and how to move the body. Since spoken instructions delivered over earplugs are often inappropriate especially in noisy environments, we envisioned small vibration motors that delivered artificial tactile feedback to those body areas that had to be adjusted. Such a wearable system could also supervise posture during daily physical activities and warn of harmful posture and movements that could lead to injuries.

Feedback on performance in sports training and on wrong posture and body movements during physical activities is often delayed or missing.

This idea motivated us to investigate if tactile stimuli could be applied as instructions during physical activities. Our research addressed

Tactile stimuli instruct how to move the body.

- if tactile stimuli exist that could represent body movements in an intuitive way,
- if these stimuli could be perceived and recognized in active situations that were physically and cognitively demanding,
- how tactile instructions compared to spoken instructions delivered over earplugs,
- how intuitive tactile instructions were rated and how well they could be learned and recalled, and
- if tactile instructions could improve the performance of athletes during sports training.

We have based our investigation on the intuitive interpretation of tactile stimuli.

In order to find tactile stimuli that could inherently represent body movements, we have investigated how young adults intuitively interpreted localized tactile pulses and directional lines rendered across their bodies, and which of the evoked sensations they associated with specific body movements. Based on the stimuli that most often prompted to move in a specific way, we have composed ten tactile motion instruction patterns that could represent body movements in various physical activities.

Tactile motion instructions are perceived in active situations.

We have conducted several empirical studies to iteratively refine these patterns and to evaluate if young adults could perceive and recognize these patterns in a stationary situation and in active situations that were physically and cognitively demanding. Our findings revealed that our volunteers could perceive tactile motion instructions almost as well as they could perceive spoken instructions delivered over earplugs. A few instructions were misinterpreted, but we assume that these mistakes were mainly caused by the experimental conditions. These conditions required the participants to respond verbally and also to perform body movements that did not always match to the movements that they already had to perform in the active situation during the experiment.

Tactile motion instructions are quickly recognized.

An important finding was that tactile motion instructions significantly reduced the response times compared to spoken instructions. Since tactile instructions directly stimulated specific body areas, the conveyed messages could be interpreted as soon as the vibration was perceived. In contrast, spoken instructions normally had to be listened in their entirety to interpret their meaning. Overall, this faster response time is an advantage in particular for sports where athletes have to quickly move their bodies.

Tactile motion instructions establish a language for teaching motor skills.

Another benefit of tactile motion instructions is that they constitute a simple language where a sequence of instructions would resemble a sequence of words or sentences in spoken languages. Our experiments revealed that young adults could recognize these compound instructions in active situations. This indicates that tactile motion instructions could be applied for teaching motor skills that are complicated and difficult to learn. For example, they could guide athletes who practice sports that would require them to perform various body movements in a specific order.

Tactile motion instructions improved performance in snowboarding.

To evaluate if this tactile language could assist in teaching motor skills, we have conducted a field study using snowboarding as example application domain. During a one-day snowboarding course, ten snowboarders learned an unfamiliar riding technique. This user group included beginners, advanced beginners, and advanced snowboarders. They experienced traditional lessons where the coach provided verbal instructions before and verbal feedback after descents, and lessons augmented with tactile motion instructions while descending the slope. All participants were able to perceive tactile motion instructions during descents, independent of their riding skills. Moreover, practicing with tactile motion instructions significantly reduced the number of snowboarding mistakes compared to traditional lessons where feedback on performance was delayed.

Overall, the young adults who participated in our user studies considered tactile motion instructions to be intuitive, and they consistently rated them to be potentially valuable as immediate feedback during training. Even so, some participants preferred to receive tactile instructions, whereas others preferred to receive spoken instructions played back over earplugs. For this reason, users should have the option to choose between tactile motion instructions and spoken instructions.

End-users valued tactile motion instructions.

This research was the first investigation into the design and evaluation of artificial tactile stimuli that could represent body movements in an intuitive way. The findings of our empirical studies have led to guidelines for designing tactile motion instructions and have resulted in a general set of tactile patterns whose meaning could be quickly learned and recalled after an extended time.

We have presented design guidelines for tactile motion instructions.

This work also described a wearable sensing and feedback device for prototyping wearable computing applications. Based on this device, we developed the first wearable assistant for snowboard training. This system could sense the movements of the snowboard and could provide tactile motion instructions that guided the snowboarder while descending the slope.

We have presented a wearable assistant for snowboard training.

The findings of this research indicate that tactile motion instructions applied while moving the body during physical activities could improve the performance of athletes and could support athletes in learning motor skills. This work has focused on snowboarding as example activity. Nevertheless, tactile motion instructions could also be applied to other physical activities where immediate feedback on wrong posture and movements is important but often delayed or missing. These activities range from sports training to daily physical activities and to rehabilitative exercises. We hope that this dissertation will inspire researchers to continue our work and to build in particular wearable computing technology that could ease the learning of challenging sports, as demonstrated in this work.

Tactile motion instructions could be applied for correcting posture and for teaching motor skills in various physical activities.

Chapter 10

Future Work

“Go for it now. The future is promised to no one.”

—*Wayne Dyer*

This work contributed to research in the field of wearable computing, of tactile communication systems, and of motor learning. We have already mentioned several challenges that we have faced, and we have addressed some opportunities for future work at appropriate passages in this thesis. In this chapter, we will recapitulate and expand on these issues.

10.1 Wearable Computing

The design and development of wearable computing applications is challenging. Wearable devices have to balance several issues, including physical robustness, portability, reliability, and power consumption. Since off-the-shelf sensing devices were designed for specific purposes, researchers and application designers often have to build custom devices and tools that address their needs. This condition can increase the threshold to prototype, to test, and to deploy wearable systems and applications, such as sensing and feedback devices for physical activities as proposed in this work.

For desktop systems, GUI development toolkits have led to a proliferation of software, and scripting and visual programming languages also enabled nonprofessionals to easily write applications. To advance the field of wearable computing, we need similar tools for rapid prototyping and testing of systems and applications. In particular, these tools should provide means to experiment with various sensors, to visualize and analyze sensor data, and they should enable developers to iteratively modify and test prototype systems under real-world conditions. For motion- and posture-based interactions, we envision systems that will be programmed by performing the required body movements. This technique—programming by

Designing wearable computing applications is challenging.

Wearable computing lacks prototyping tools.

demonstration—would hide application code and sensor data from designers, and would also empower nonprofessionals to quickly prototype and explore wearable applications [Hartmann et al., 2007].

We need sport technologies for sensing and analyzing the athlete's performance.

This work has proposed wearable technology for physical activities that could automatically analyze posture and body movements and that could provide tactile instructions for corrections. As an example, we have demonstrated posture and motion recognition for snowboarding in realtime, based on a custom-built sensing system and an off-the-shelf mobile device. We have also demonstrated that tactile instructions could be applied automatically during descents, considering the snowboarder's weight distribution. Even so, to deploy wearable systems that can provide feedback on incorrect posture and movements during sports training, it is necessary to sense body movements and to build a posture and motion model that can be evaluated according to specific sports techniques in realtime.

User independent motion and posture recognition is challenging in realtime.

The algorithms that we have developed set thresholds on sensor signals to recognize simple movements, such as transitions between stretched or flexed legs, or increased weight distribution towards the toes or the heels. This approach was fast and could accurately classify live sensor data obtained during descents. Even so, this method cannot classify movements that continuously change over time. To recognize such movements, machine learning techniques are required, as demonstrated by Kwon and Gross [2005] and Kunze et al. [2006], but these techniques do not yet run in realtime. Overall, we envision wearable devices that can determine posture and body movements independent of the athlete and of the performed activity, similar to speech recognition systems that can process speech independent of the speaker's voice characteristics and background noise.

Posture and motion models for sports training are required.

Also, our systems did not detect riding mistakes but relied on the transitions between the recognized postures and used the correct posture sequence that had to be performed as basis for deciding when and which instructions to trigger during the descent. Transitions between postures, however, cannot reveal incorrect sequences of continuous body movements. To analyze such movements necessitates a motion model that can describe the correct movement patterns. Such a model could be based, for example, on body movements that were performed by instructors.

10.2 Tactile Motion Instructions

The design space of tactile motion instructions has not been fully explored yet.

This work is the first investigation into artificial tactile stimuli that could represent body movements in an intuitive way. Our findings have lead to a first set of guidelines for designing tactile motion instruction patterns. This design space should be explored further to determine which other parameters for tactile information transfer could be appropriate for composing messages that could represent body movements, considering stationary and active situations, and various physical activities.

Our initial study on the intuitive interpretation of tactile stimuli relied on an open response paradigm such that our participants could state any meaning that they associated with a stimulus. Although this approach allowed us to collect unbiased answers, some responses were often vague and difficult to classify. A forced-choice paradigm, based on a set of predetermined body movements as answers, might help refine the view which tactile stimuli would be suitable for representing a specific body movement.

A forced-choice paradigm could help refine the interpretation of tactile stimuli.

We have focused on body locations that seemed appropriate for representing a specific body movement, but we did not fully explore the available skin area. Also, we have investigated localized pulses and directional lines that were based on certain timing values for pulses and on a constant vibration intensity. Future studies could explore with which body movements other sensations are associated, and if the characteristics of these alternative tactile stimuli can be perceived and differentiated in active situations.

Alternative parameters for tactile messages

For example, the timing values for directional lines can influence the perceived smoothness or the length of the evoked sensations [Cholewiak and Collins, 2000]. Quickly increasing and decreasing intensity levels might also evoke smooth sensations, which might represent fluid instead of jerky body movements. The stimulus duration and the intensity might encode how quick or wide to perform the movement. In addition, strong pulses delivered across a large area might be more appropriate for representing instructions based on the push metaphor than soft pulses, whereas directional lines that extend over the entire body might result in more expressive sensations than short lines that stimulate either the torso or the thighs. For physical activities that do not involve high cognitive and physical load such that variations in these parameters could be differentiated, tactile patterns might exploit such stimulus characteristics for encoding messages.

Tactile motion instructions could exploit other durations, intensities, and body locations.

Moreover, this work has initially focused on three localized pulses of 400 ms duration and on directional lines of 1300 ms duration. For single instructions, these durations are short, and they would allow athletes to quickly react upon perceiving the vibration. For compound instructions, however, the total duration required for perceiving sequential messages might be too long when body movements have to be quickly executed, as was the case in our study on learning of motor skills in snowboarding. Future work should investigate if athletes can perceive shorter timing values and fewer number of pulses in active situations. These values, however, could vary depending on the physical activity and on the user's cognitive abilities to paying attention to artificial tactile stimuli. Also, we have focused on compound instructions that consisted of two sequential messages. Future studies should evaluate compounds that consist of longer sequences.

Compound instructions need further investigation.

One challenge that we have faced was to accurately measure if our participants could perceive and identify tactile motion instructions in active situations. For this reason, we asked our participants to utter their responses. This experimental condition was not optimal for evaluating tactile motion instructions because some participants tended to mix up the messages when responding verbally. Moreover, they also had to interpret randomly applied

Automatic motion and posture classification could help evaluate tactile motion instructions.

instructions that did not always match to the movements that they already had to perform in the investigated activities. In order to avoid verbal responses and in order to provide instructions that do not interfere with other body movements, future studies should consider technology that can automatically sense and classify body movements.

Feedback displays that create realistic pushing and pulling sensations

An interesting finding of our studies was that our volunteers preferred to move either towards or away from the vibration. Therefore, we have based tactile motion instructions on two encoding metaphors: stimuli that pulled the body; and stimuli that pushed the body. Nevertheless, instead of assigning different meanings to the same stimulus, which actually evokes the same sensation on the skin, wearable displays should create pushing and pulling sensations that feel realistic. Such devices do not yet exist, except for a force-feedback handheld device that creates pulling sensations as navigation cues [Amemiya et al., 2008].

Stimulating key muscles required for performing movements.

Also, instead of indicating the direction in which to move the body by stimulating the body area that has to be moved, a different approach could directly stimulate the muscles that would be required for performing the movements. Related work indicated that this approach was less effective and less intuitive for representing hand rotation [Jansen et al., 2004]. Even so, this finding cannot be generalized to other body movements and should be investigated further.

10.3 Motor Learning

How do tactile motion instructions influence the attentional focus of athletes?

In the last two decades, research in motor learning has shown that the wording of feedback and of instructions can influence an athlete's performance. To improve the performance and learning of motor skills, the wording should guide the learner's attention to the outcome of the performed movements instead of to the body and how to coordinate body movements. Since tactile instructions directly stimulate the body, future work should examine if these artificial stimuli do not negate the effect that the wording of the conveyed message is supposed to induce.

Tactile motion instructions have to be evaluated in other physical activities.

During a one-day snowboarding course, we have compared realtime tactile motion instructions during descents to the traditional teaching method where students only received spoken instructions before and spoken feedback after exercises. Although our findings indicated that tactile instructions could support athletes in learning motor skills, long-term studies should investigate how effective this realtime feedback is compared to traditional teaching methods. Tactile instructions should also be evaluated in other physical activities, such as dancing, martial arts, and rehabilitative exercises. Moreover, we have evaluated these instructions with young adults and with few users. Future studies should consider larger user groups, and they should include users of other age cohorts because the ability to learn, to perceive, and to interpret tactile stimuli could vary between people.

Future work should also compare tactile motion instructions to spoken instructions for learning motor skills, and could investigate if tactile motion instructions that complement spoken instructions are beneficial to learning. Also, since spoken messages could be too long as realtime instructions, shorter messages should be explored, such as single words. This raises the questions how short the wording of a message could be to remain effective as an instruction, and if athletes would prefer to map a single spoken word or a brief tactile stimulus to a specific body movement.

Comparing tactile
to spoken
instructions

One intriguing application for wearable training assistants is to sense and to transmit the instructor's body movements to the athletes' body. For example, if the coach flexed the legs during demonstrations, the athletes would perceive tactile instructions at their thighs that signaled to flex the legs. Besides observing the coach during demonstrations, this direct tactile feedback would allow athletes to immediately experience how the instructor moves and which movement sequences are correct.

Athletes could
experience the
instructor's body
movements.

Part IV

Appendix

Appendix A

Motor Shield Schematic

The developed motor shield was a printed circuit board that could be plugged on top of the Arduino BT. This board could controls six actuators by pulse width modulation [Barr, 2001]. The circuit of the motor shield (see Fig. A.1) comprised the following electrical components:

- Power MOSFET IRLD024
- 100 Ω resistors
- 100 nF capacitor
- 1 μF electrolytic capacitor

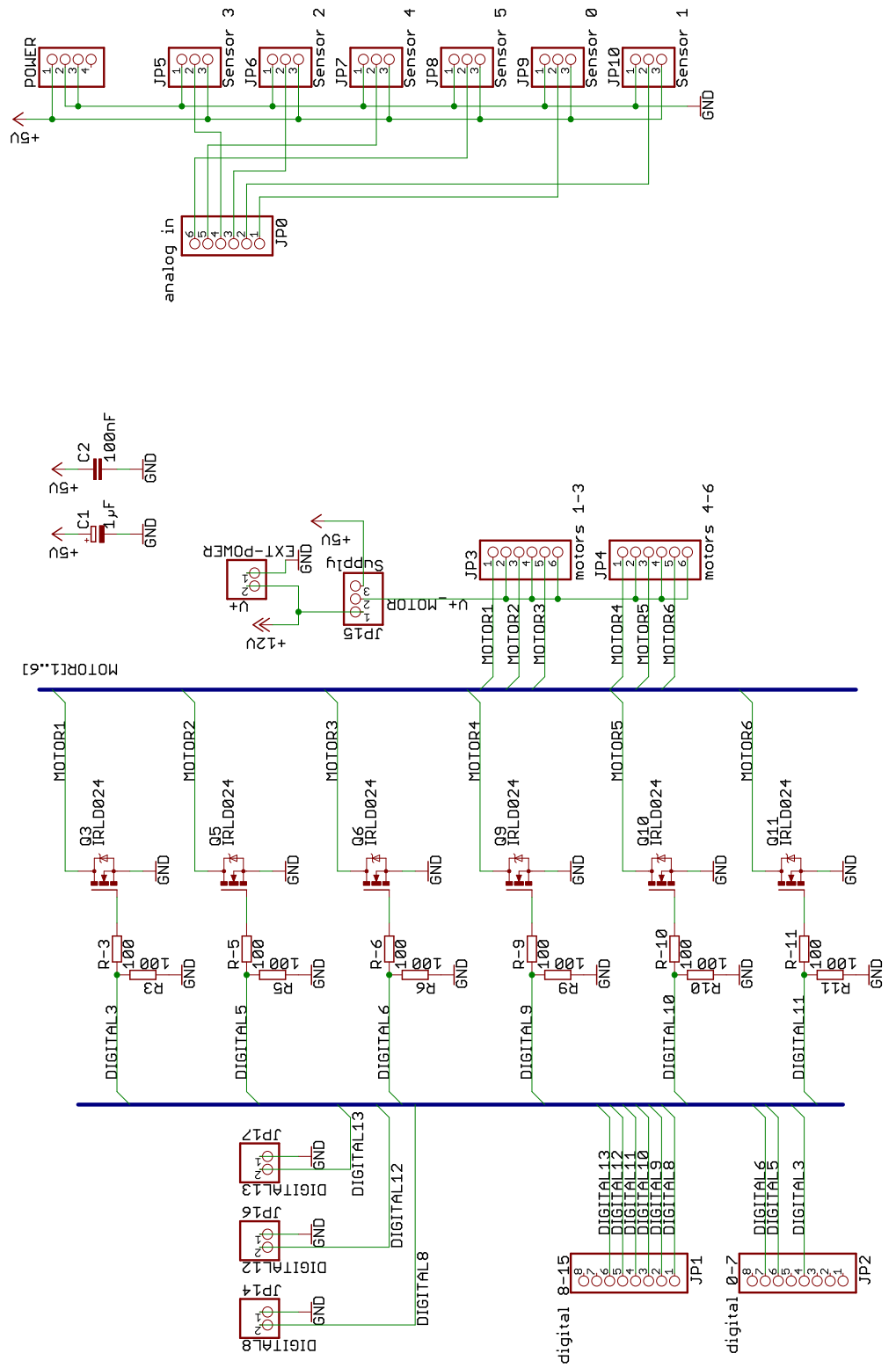


Figure A.1: The circuit schematic of the motor shield.

Appendix B

Post-Study Questionnaire: Comparing Tactile Instructions to Audio Instructions While Snowboarding

Your Personal Data

Thank you very much for participating in our user study on real-time audio and tactile instructions. Please take 15 minutes time to answer the following questions. Please note that if we use any of your responses in reports or presentations, your real name will not be used, and any personally identifying data will be changed or omitted.

Your Personal Data

What is your name?

Are you a boy or a girl?

How old are you?

What is your profession?

Did you experience artificial tactile instructions before this study?

- No
- Yes

Do you have a disease or skin damages that could influence your tactile perception?

- No
- Yes

How would you grade your snowboarding skills?

- Beginner
- Advanced beginner
- Advanced
- Proficient
- Expert

Audio instructions

I could understand audio instructions during the ride (quality of audio):

- Very Good
- Good
- Barely Acceptable
- Poor
- Very Poor

I could map audio instructions to body movements:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Having perceived an audio instruction, I felt incited to perform the movement:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Audio instructions distracted from focusing on riding:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

I think audio instructions are helpful during the ride:

- Strongly Agree
- Agree

- Undecided
- Disagree
- Strongly Disagree

Tactile instructions

I could perceive tactile instructions during the ride:

- Very Good
- Good
- Barely Acceptable
- Poor
- Very Poor

The sensation of tactile instructions was:

- Very pleasant
- Somewhat pleasant
- Neither pleasant nor unpleasant
- Somewhat unpleasant
- Very unpleasant

I could map tactile instructions to body movements:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Tactile instructions were intuitive:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Having perceived a tactile instruction, I felt incited to perform the movement:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Tactile instructions distracted from focusing on riding:

- Strongly Agree

- Agree
- Undecided
- Disagree
- Strongly Disagree

I think tactile instructions are helpful during the ride:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Your overall impression

Which feedback channel do you prefer for corrections? Please explain why.

- Audio
- Tactile

Wearing the system was...

- Very comfortable
- Somewhat comfortable
- Neither comfortable nor uncomfortable
- Somewhat uncomfortable
- Very uncomfortable

Further comments:

Appendix C

Post-Study Questionnaire: Perception of Tactile Instructions While Horseback Riding

Your Personal Data

Thank you very much for participating in our user study on real-time tactile instructions. Please take 15 minutes time to answer the following questions. Please note that if we use any of your responses in reports or presentations, your real name will not be used, and any personally identifying data will be changed or omitted.

Your Personal Data

What is your name?

Are you a boy or a girl?

How old are you?

What is your profession?

Did you experience artificial tactile instructions before this study?

- No
- Yes

Do you have a disease or skin damages that could influence your tactile perception?

- No
- Yes

How would you grade your equestrian skills?

- Beginner
- Advanced beginner
- Advanced
- Proficient
- Expert

Tactile instructions

I could perceive tactile instructions during the ride:

- Very Good
- Good
- Barely Acceptable
- Poor
- Very Poor

The sensation of tactile instructions was:

- Very pleasant
- Somewhat pleasant
- Neither pleasant nor unpleasant
- Somewhat unpleasant
- Very unpleasant

I could map tactile instructions to body movements:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Tactile instructions were intuitive:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Having perceived a tactile instruction, I felt incited to perform the movement:

- Strongly Agree
- Agree
- Undecided
- Disagree

Strongly Disagree

Tactile instructions distracted from focusing on riding:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

I think tactile instructions are helpful during the ride:

- Strongly Agree
- Agree
- Undecided
- Disagree
- Strongly Disagree

Your overall impression

Wearing the system was...

- Very comfortable
- Somewhat comfortable
- Neither comfortable nor uncomfortable
- Somewhat uncomfortable
- Very uncomfortable

Further comments:

Appendix D

Post-Study Questionnaire: Learning New Motor Skills

Thank you very much for participating in our user study on real-time tactile instructions. Please take 15 minutes time to answer the following questions. Please note that if we use any of your responses in reports or presentations, your real name will not be used, and any personally identifying data will be changed or omitted.

Your Personal Data

What is your name?

Are you a boy or a girl?

How old are you?

What is your profession?

Which sports other than snowboarding do you practice?

How often do you practice these other sports?

- Never
- Seldom
- Sometimes
- Often
- Regularly

Your Previous Experience With Artificial Tactile Feedback

Did you experience artificial tactile feedback before this study (for example, other studies on tactile feedback)?

- No
- Yes

Do you have a disease or skin damages that could influence your tactile perception (for example, burns of the skin)?

- No
- Yes

Your Snowboarding Skills

For how many years do you snowboard?

How often do you snowboard on average per year?

- Up to 1 week
- 1–2 weeks
- 2–3 weeks
- 3–4 weeks
- More than 4 weeks

How would you grade your overall snowboarding skills?

- Beginner
- Advanced beginner
- Advanced
- Proficient
- Expert

Did you participate in a course (3 or more days) to improve your skills?

- No
- Yes

Have you tried to ride switch before this study?

- No
- Yes

Would you say it is difficult to learn to ride switch?

- I strongly disagree
- I disagree
- Don't know
- I agree
- I strongly agree

How much would you say that you improved your skills in riding switch during this study?

- Not at all
- Very little

-
- Somewhat
 - Much
 - To a great extent

How would you rate your skills in riding switch BEFORE participating in this study?

- Very poor
- Poor
- Barely acceptable
- Good
- Very good

How would you rate your skills in riding switch AFTER participating in this study?

- Very poor
- Poor
- Barely acceptable
- Good
- Very good

Real-time Tactile Instructions During Your Ride

The tactile instructions that you have received during descents indicated important body movements for riding switch with correct posture.

When did you get tactile instructions during the ride?

- In the morning, before the break
- In the afternoon, after the break

How well did you perceive tactile instructions during the ride?

- Very poor
- Poor
- Barely acceptable
- Good
- Very good

Before the descent, your instructor explained how to correctly ride switch. Would you say that tactile instructions during the ride corresponded to the spoken instructions?

- Not at all
- Very little
- Somewhat
- Much
- To a great extent

Would you say that tactile instructions were helpful for you to ride switch with correct posture?

- It absolutely made no sense to me
- It was no help
- Don't know
- It was useful
- It was a strong help

Would you say that riding with tactile instructions motivated you to try harder to correctly ride switch as opposed to riding without tactile instructions?

- Not at all
- Very little
- Somewhat
- Much
- To a great extent

Would you say that riding with tactile instructions improved the quality of your ride as opposed to riding switch without tactile instructions?

- Not at all
- Very little
- Somewhat
- Much
- To a great extent

Would you say that tactile instructions during the ride distracted you from following the spoken instructions from your instructor?

- I strongly disagree
- I disagree
- Don't know
- I agree
- I strongly agree

What did you NOT like about tactile instructions during the ride? Write whatever you think.

What did you like about tactile instructions during the ride? Write whatever you think.

Real-time Tactile Instructions For Learning New Riding Techniques

Imagine that you were learning another snowboarding technique that you have never tried before (Hochschwung/Tiefschwung, Carving, etc.).

How important would you consider tactile instructions that indicated

correct posture during the ride?

- Unimportant
- Of little importance
- Moderately important
- Important
- Very important

I would prefer to learn new techniques only with spoken instructions before the descent:

- I strongly disagree
- I disagree
- Don't know
- I agree
- I strongly agree

I would prefer to learn new techniques with spoken instructions before the descent and with tactile instructions during the ride:

- I strongly disagree
- I disagree
- Don't know
- I agree
- I strongly agree

I would prefer tactile instructions that indicated correct posture only if I did something wrong.

- I strongly disagree
- I disagree
- Don't know
- I agree
- I strongly agree

Additional comments: Write whatever you think.

Appendix E

The Structure of Languages

In this appendix, we will briefly describe the formal syntactic notation that defines the structure of formal languages. Additional information on this topic can be found in Rozenberg and Salomaa [1997].

A language is based on a finite *alphabet* Σ . The elements of the alphabet are called *letters* or *symbols*. A finite sequence of zero or more letters is called a *word* or a *string* ($w = u_1u_2\dots u_n$, $n \in \mathbb{N}$, $u_i \in \Sigma$). The *empty word* is called λ or ϵ (w^0). The concatenation of two words v and w form the word vw . Σ^* is the infinite set of all finite words over Σ . $\Sigma^+ = \Sigma^* \setminus \{\lambda\}$ is the infinite set of all nonempty finite words. Based on these concepts, a formal *language* over Σ is defined as a finite or infinite subset of Σ^* . This subset contains finite words from its alphabet.

“A language is a set of finite words of symbols from a finite alphabet.”

All languages, in particular written languages, can be thought of as formal languages. Consider the Latin alphabet reduced to lowercase letters and whitespace $\Sigma = \{a, b, c, \dots, z, _ \}$. This set of symbols suffices to describe words in natural languages, such as in English and German. For example, “bbb”, “star”, and “the sun is shining” are words over Σ . One finite language over this alphabet is $L = \{\text{bbb, star, the sun is shining}\}$, which we define by listing all of its words.

An example language

In the example language L given above, “bbb” is a valid word from L but its form and meaning would not make sense in spoken languages, such as in English. Formal grammars can be used to define how to form strings from the elements of the alphabet. We will not discuss this issue here as it is not relevant for our work.

Formal grammars

Bibliography

- Jacopo Aleotti, Stefano Caselli, and Monica Reggiani. Multimodal user interface for remote object exploration with sparse sensory data. In *Proceedings of the 11th IEEE International Workshop on Robot and Human Interactive Communication*, pages 41–46, 2002.
- Tomohiro Amemiya, Hideyuki Tomohiro, and Taro Maeda. Lead-Me Interface for a Pulling Sensation from Hand-held Devices. *ACM Transactions on Applied Perception*, 5(3):1–17, 2008.
- Animazoo. IGS-190-M, 2004. URL <http://www.animazoo.com/>.
- Apple. Nike + iPod, April 2008. URL <http://www.apple.com/ipod/nike/>.
- Ascension Technology Cooperation. Flock of Birds, 2008. URL <http://www.ascension-tech.com/>.
- Ramy Asselin, Guillermo Ortiz, Jonathan Pui, Saim Smailagic, and Christian Kissling. Implementation and Evaluation of the Personal Wellness Coach. In *IWSAWC '05: Proceedings of the 5th International Workshop on Smart Appliances and Wearable Computing*, pages 529–535, Washington, DC, USA, 2005. IEEE Computer Society.
- Atmel Corporation. ATmega168, 2009. URL http://www.atmel.com/dyn/resources/prod_documents/doc2545.pdf.
- Audiologic Engineering Corporation (AEC). Tactaid, 1982. URL <http://www.tactaid.com/>.
- Ryan Aylward and Joseph A. Paradiso. Senseable: A Wireless, Compact, Multi-User Sensor System for Interactive Dance. In *NIME '06: Proceedings of the 2006 Conference on New Interfaces for Musical Expression*, pages 134–139, Paris, France, France, 2006. IRCAM.
- A. Baca and P. Kornfeind. Rapid Feedback Systems for Elite Sports Training. *IEEE Pervasive Computing*, 5(4):70–76, 2006.
- Ronald M. Baecker, Jonathan Grudin, William A. S. Buxton, and Saul Greenberg. *Readings in Human-Computer Interaction: Toward the Year 2000*. Morgan Kaufmann, 1995.
- Rafael Ballagas. *Bringing Iterative Design To Ubiquitous Computing: Interaction Techniques, Toolkits, and Evaluation Methods*. PhD thesis, Department of Computer Science, RWTH Aachen University, August 2007.

- Rafael Ballagas, Faraz Memon, René Reiners, and Jan Borchers. iStuff Mobile: Rapidly Prototyping New Mobile Phone Interfaces for Ubiquitous Computing. In *CHI '07: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1107–1116, New York, NY, USA, 2007. ACM Press.
- David Bannach, Oliver Amft, and Paul Lukowicz. Rapid Prototyping of Activity Recognition Applications. *IEEE Pervasive Computing*, 7(2): 22–31, 2008.
- Massimo Banzi, David Cuartielles, Tom Igoe, Gianluca Martino, David Mellis, and Nicholas Zambetti. Arduino, 2005. URL <http://www.arduino.cc/>.
- Ling Bao and Stephen S. Intille. Activity Recognition from User-Annotated Acceleration Data. In *PERVASIVE '04: Proceedings of the 2nd International Conference on Pervasive Computing*, volume 3001 of *Lecture Notes in Computer Science*, pages 1–17. Springer, April 21-23 2004.
- Michael Barr. Pulse Width Modulation. *Embedded Systems Programming*, 14(10):103–104, September 2001.
- Len Bass, Chris Kasabach, Richard Martin, Dan Siewiorek, Asim Smailagic, and John Stivoric. The Design of a Wearable Computer. In *CHI '97: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 139–146, New York, NY, USA, 1997. ACM Press.
- Michael Beigl and Hans Gellersen. Smart-Its: An Embedded Platform for Smart Objects. In *SOC '03: Proceedings of the Smart Objects Conference*, May 2003.
- Mohamed Benali-Khoudja, Moustapha Hafez, Amaury Sautour, and Sylvie Jumpertz. Towards A New Tactile Language to Communicate Emotions. In *Proceedings of the IEEE International Conference on Mechatronics and Automation*. IEEE Computer Society, July 2005.
- Ari Y. Benbasat and Joseph A. Paradiso. An Inertial Measurement Framework for Gesture Recognition and Applications. In Ipke Wachsmuth and Timo Sowa, editors, *GW '01: International Gesture Workshop on Gesture and Sign Languages in Human-Computer Interaction*, number 2298 in LNCS, pages 9–20, London, UK, April 18-20 2002. Springer.
- Jan Beutel, Oliver Kasten, Friedmann Mattern, Kay Römer, Frank Siegemund, and Lothar Thiele. Prototyping Wireless Sensor Network Applications with BTnodes. In *EWSN '04: Proceedings of the 1st European Workshop on Sensor Networks*, 2920, pages 323–338, Berlin / Heidelberg, 2004. Springer-Verlag.
- Anu Bhargava, Michael Scott, Ryan Traylor, Roy Chung, Kimberly Mrozek, Jonathan Wolter, and Hong Z. Tan. Effect of Cognitive Load on Tactor Location Identification in Zero-g. In *WHC '05: Proceedings of the 1st Joint EuroHaptics Conference and the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 56–62, Washington, DC, USA, 2005. IEEE Computer Society.

- Edward A. Bilodeau and Ina McD. Bilodeau. Variable frequency of knowledge of results and the learning of a simple skill. *Journal of experimental psychology*, 55(4):379, 1958.
- Edward A. Bilodeau, Ina M. Bilodeau, and Donald A. Schumsky. Some effects of introducing and withdrawing knowledge of results early and late in practice. *Journal of Experimental Psychology*, 58:142–144, 1959.
- Meera M. Blattner, Denise A. Sumikawa, and Robert M. Greenberg. Earcons and Icons: Their Structure and Common Design Principles. *Human Computer Interaction*, 4(1):11–44, 1989.
- Jérémy Bluteau, Sabine Coquillart, Yohan Payan, and Edouard Gentaz. Haptic Guidance Improves the Visuo-Manual Tracking of Trajectories. *PLoS ONE*, 3(3), March 2008.
- BodyMedia. GoWear fit, November 2008. URL <http://www.bodymedia.com/>.
- Chris Braisby. The Ski Coach, 2005. URL <http://www.theskicoach.com/>.
- Scott Brave and Andrew Dahley. inTouch: A Medium for Haptic Interpersonal Communication. In *CHI '97: Extended Abstracts of the International Conference on Human Factors in Computing Systems*, pages 363–364, New York, NY, USA, 1997. ACM Press.
- Stephen Brewster, Joanna Lumsden, Marek Bell, Malcolm Hall, and Stuart Tasker. Multimodal ‘Eyes-Free’ Interaction Techniques for Wearable Devices. In *CHI '03: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 473–480, New York, NY, USA, 2003. ACM Press.
- Stephen A. Brewster and Lorna M. Brown. Tactons: Structured Tactile Messages for Non-Visual Information Display. In *AUIC '04: Proceedings of the 5th Conference on Australasian User Interface*, pages 15–23, Darlinghurst, Australia, 2004. Australian Computer Society, Inc.
- Stephen A. Brewster, Peter C. Wright, and Alistair D. N. Edwards. Experimentally Derived Guidelines for the Creation of Earcons. In *HCI '95: Adjunct Proceedings of HCI*, pages 155–159. Springer, 1995.
- Matthew Brodie, Alan Walmsley, and Wyatt Page. Fusion Motion Capture: A Prototype System using Inertial Measurement Units and GPS for the Biomechanical Analysis of Ski Racing. *Sports Technology*, 1:17–28, 2008.
- Lorna M. Brown. *Tactons: Structured Vibrotactile Messages for Non-Visual Information Display*. PhD thesis, Department of Computing Science, University of Glasgow, April 2007.
- Brüel & Kjær. Piezoelectric accelerometer type 4393 V, 2009. URL <http://www.bksv.com/>.
- Davide Brunelli, Elisabetta Farella, Laura Rocchi, Marco Dozza, Lorenzo Chiari, and Luca Benini. Bio-feedback System for Rehabilitation Based on a Wireless Body Area Network. In *PERCOMW '06: Proceedings of*

- the 4th annual IEEE International Conference on Pervasive Computing and Communications Workshops*, pages 527–531, Washington, DC, USA, 2006. IEEE Computer Society.
- Leah Buechley. A Construction Kit for Electronic Textiles. In *ISWC '06: Proceedings of the 10th IEEE International Symposium on Wearable Computers*, pages 83–90. IEEE Computer Society, 2006.
- Leah Buechley, Mike Eisenberg, Jaime Catchen, and Ali Crockett. The Lily-Pad Arduino: Using Computational Textiles to Investigate Engagement, Aesthetics, and Diversity in Computer Science Education. In *CHI '08: Proceeding of the SIGCHI Conference on Human Factors in Computing Systems*, pages 423–432, New York, NY, USA, 2008. ACM Press.
- William A. Buxton and Richard Sniderman. Iteration in the Design of the Human-Computer Interface. In *Proceedings of the 13th Annual Meeting of the Human Factors Association of Canada*, pages 72–81. HFAC, 1980.
- Alexandru Caracas, Ernst A. Heinz, Philipp Robbel, Amrish Singh, Frank Walter, and Paul Lukowicz. Real-time Sensor Processing with Graphical Data Display in Java. In *ISSPIT '03: Proceedings of the 3rd IEEE International Symposium on Signal Processing and Information Technology*, pages 62–65. IEEE, 2003.
- Sylvain Cardin, Daniel Thalmann, and Frédéric Vexo. Wearable System for Mobility Improvement of Visually Impaired People. *The Visual Computer*, 23(2):109–118, 2006a.
- Sylvain Cardin, Frédéric Vexo, and Daniel Thalmann. Vibro-Tactile Interface for Enhancing Piloting Abilities During Long Term Flight. *Journal of Robotics and Mechatronics*, 18(4):381–391, 2006b.
- Michael J. Caruso. Applications of Magnetic Sensors for Low Cost Compass Systems. In *Position Location and Navigation Symposium*, pages 177–184. IEEE, 2000.
- Alvaro Cassinelli, Carson Reynolds, and Masatoshi Ishikawa. Augmenting Spatial Awareness with Haptic Radar. In *ISWC '06: Proceedings of the 10th IEEE International Symposium on Wearable Computers*, pages 61–64. IEEE Computer Society, October 2006.
- Andrew Chan, Karon MacLean, and Joanna McGrenere. Learning and Identifying Haptic Icons under Workload. In *WHC '05: Proceedings of the 1st Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 432–439, Washington, DC, USA, 2005. IEEE Computer Society.
- Angela Chang, Sile O'Modhrain, Rob Jacob, Eric Gunther, and Hiroshi Ishii. ComTouch: Design of a Vibrotactile Communication Device. In *DIS '02: Proceedings of the 4th Conference on Designing Interactive Systems*, pages 312–320, New York, NY, USA, 2002. ACM Press.
- Elaine Chen and Beth Marcus. Force Feedback for Surgical Simulation. *Proceedings of the IEEE*, 86(3):524–530, 1998.

- Ed H. Chi, Jin Song, and Greg Corbin. “Killer App” of Wearable Computing: Wireless Force Sensing Body Protectors for Martial Arts. In *UIST '04: Proceedings of the 17th annual ACM Symposium on User Interface Software and Technology*, pages 277–285, New York, NY, USA, October 2004. ACM Press.
- Ed H. Chi, Gaetano Borriello, Guerney Hunt, and Nigel Davies. Guest Editors’ Introduction: Pervasive Computing in Sports Technologies. *IEEE Pervasive Computing*, 4(3):22–25, 2005.
- Roger W. Cholewiak and Amy A. Collins. Sensory and Physiological Bases of Touch. In Morton A. Heller and William Schiff, editors, *The Psychology of Touch*, pages 23–60. Lawrence Erlbaum, 1991.
- Roger W. Cholewiak and Amy A. Collins. Vibrotactile pattern discrimination and communality at several body sites. *Perception & Psychophysics*, 57(5):724–737, 1995.
- Roger W. Cholewiak and Amy A. Collins. The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mode. *Perception & Psychophysics*, 62(6):1220–1235, 2000.
- Roger W. Cholewiak and Amy A. Collins. Vibrotactile localization on the arm: Effects of place, space, and age. *Perception & Psychophysics*, 65(7):1058–1077, 2003.
- Roger W. Cholewiak and Michael Wollowitz. The design of vibrotactile transducers. In Ian R. Summers, editor, *Tactile Aids for the Hearing Impaired*, pages 57–82. Whurr Publishers Ltd., London, 1992.
- Tanzeem Choudhury, Gaetano Borriello, Sunny Consolvo, Dirk Haehnel, Beverly Harrison, Bruce Hemingway, Jeffrey Hightower, Predrag “Pedja” Klasnja, Karl Koscher, Anthony LaMarca, James A. Landay, Louis LeGrand, Jonathan Lester, Ali Rahimi, Adam Rea, and Danny Wyatt. The Mobile Sensing Platform: An Embedded Activity Recognition System. *IEEE Pervasive Computing*, 7(2):32–41, 2008.
- Marcelo Coelho and Pattie Maes. Sprout I/O: A Texturally Rich Interface. In *TEI '08: Proceedings of the 2nd International Conference on Tangible and Embedded Interaction*, pages 221–222, New York, NY, USA, 2008. ACM Press.
- Cooper Aerobics Center, 2010. URL <http://www.cooperaerobics.com/>.
- James C. Craig. Difference threshold for intensity of tactile stimuli. *Perception & Psychophysics*, 11(2):150–152, 1972.
- James C. Craig and Carl E. Sherrick. Dynamic tactile displays. In William Schiff and Emerson Foulke, editors, *Tactual perception: A sourcebook*, pages 209–233. Cambridge University Press, 1982.
- Carolina Cruz-Neira, Daniel J. Sandin, Thomas A. DeFanti, Robert V. Kenyon, and John C. Hart. The CAVE: Audio Visual Experience Automatic Virtual Environment. *Communications of the ACM*, 35(6):64–72, 1992.

- CuteCircuit. The Hug Shirt, 2010. URL <http://www.cutecircuit.com/products/thehugshirt/>.
- CyberGlove Systems. Cybertouch, 2007. URL <http://www.cyberglovesystems.com/>.
- Deutscher Ski-Verband (DSV), 2009. URL <http://www.deutscherskiverband.de>.
- Deutscher Verband für das Skilehrwesen, Interski Deutschland. *Snowboard-Lehrplan*. Blv Buchverlag, München, September 2003.
- Rich DeVaul, Michael Sung, Jonathan Gips, and Alex Pentland. MIThril 2003: Applications and Architecture. In *ISWC '03: Proceedings of the 7th IEEE International Symposium on Wearable Computers*, pages 4–11, Washington, DC, USA, 2003. IEEE Computer Society.
- Anind K. Dey. Understanding and Using Context. *Personal and Ubiquitous Computing*, 5(1):4–7, 2001.
- Anind K. Dey, Daniel Salber, Gregory D. Abowd, and Masayasu Futakawa. The Conference Assistant: Combining Context-Awareness with Wearable Computing. In *ISWC '99: Proceedings of the 3rd IEEE International Symposium on Wearable Computers*, pages 21–28. IEEE Computer Society, 1999.
- Anind K. Dey, Gregory D. Abowd, and Daniel Salber. A Conceptual Framework and a Toolkit for Supporting the Rapid Prototyping of Context-Aware Applications. *Human-Computer Interaction*, 16(2-4):97–166, 2001.
- Anind K. Dey, Timothy Sohn, Sara Streng, and Justin Kodama. iCAP: Interactive Prototyping of Context-Aware Applications. In *PERVASIVE '06: Proceedings of the 4th International Conference on Pervasive Computing*, number 3968 in LNCS, pages 254–271. Springer, 2006.
- Paul Dourish. What we talk about when we talk about context. *Personal and Ubiquitous Computing*, 8(1):19–30, 2004.
- Lucy E. Dunne and Barry Smyth. Psychophysical Elements of Wearability. In *CHI '07: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 299–302, New York, NY, USA, 2007. ACM Press.
- Engineering Acoustics Inc. C2 tactor, 2010. URL <http://www.eaiinfo.com/>.
- Mario J. Enriquez and Karon E. MacLean. The Hapticon Editor: A Tool in Support of Haptic Communication Research. In *HAPTICS '03: Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 356–362, Washington, DC, USA, 2003. IEEE Computer Society.

- Mario J. Enriquez, Karon E. MacLean, and Christian Chita. Haptic Phonemes: Basic Building Blocks of Haptic Communication. In *ICMI '06: Proceedings of the 8th International Conference on Multimodal Interfaces*, pages 302–309, New York, NY, USA, 2006. ACM Press.
- Sevgi Ertan, Clare Lee, Abigail Willets, Hong Tan, and Alex Pentland. A Wearable Haptic Navigation Guidance System. In *ISWC '98: Proceedings of the 2nd IEEE International Symposium on Wearable Computers*, pages 164–165, Washington, DC, USA, 1998. IEEE Computer Society.
- Jonny Farrington, Andrew J. Moore, Nancy Tilbury, James Church, and Pieter D. Biemond. Wearable Sensor Badge and Sensor Jacket for Context Awareness. In *ISWC '99: Proceedings of the 3rd IEEE International Symposium on Wearable Computers*, pages 107–113, Washington, DC, USA, 1999. IEEE Computer Society.
- BJ Fogg, Lawrence D. Cutler, Perry Arnold, and Chris Eisbach. Hand-Jive: A Device for Interpersonal Haptic Entertainment. In *CHI '98: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 57–64, New York, NY, USA, 1998. ACM Press/Addison-Wesley Publishing Co.
- Frank A. Geldard. Adventures in Tactile Literacy. *The American Psychologist*, 12(3):115–124, 1957.
- Frank A. Geldard. Some Neglected Possibilities of Communication. *Science*, 131(3413):1583–1588, 1960.
- Frank A. Geldard. Cutaneous coding of optical signals: The optohapt. *Perception & Psychophysics*, 1:377–381, 1966.
- Frank A. Geldard. *Sensory Saltation: Metastability in the Perceptual World*. Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1975.
- Frank A. Geldard. The Mutability of Time and Space on the Skin. *The Journal of the Acoustical Society of America*, 77(1):233–237, 1985.
- Frank A. Geldard and Carl E. Sherrick. Multiple Cutaneous Stimulation: The Discrimination of Vibratory Patterns. *The Journal of the Acoustical Society of America*, 37:797–801, 1965.
- Frank A. Geldard and Carl E. Sherrick. The Cutaneous “Rabbit”: A Perceptual Illusion. *Science*, 178(4057):178–179, 1972.
- Francine Gemperle, Chris Kasabach, John Stivoric, Malcolm Bauer, and Richard Martin. Design for Wearability. In *ISWC '98: Proceedings of the 2nd IEEE International Symposium on Wearable Computers*, pages 116–122. IEEE Computer Society, 1998.
- Francine Gemperle, Nathan Ota, and Dan Siewiorek. Design of a Wearable Tactile Display. In *ISWC '01: Proceedings of the 5th IEEE International Symposium on Wearable Computers*, pages 5–12, Washington, DC, USA, 2001. IEEE Computer Society.

- Vadim Gerasimov. Hoarder Board, 2002. URL <http://vadim.oversigma.com/Hoarder/Hoarder.htm>.
- Georg A. Gescheider, S. J. Bolanowski, and Ronald T. Verrillo. Temporal relations in cutaneous stimulation. *Cutaneous communication systems and devices*, pages 33–37, 1974.
- E. Bruce Goldstein. *Wahrnehmungspsychologie*. Spektrum-Akademischer Verlag, 2. edition, 2002.
- John D. Gould and Clayton Lewis. Designing for Usability: Key Principles and What Designers Think. *Communications of the ACM*, 28(3):300–311, 1985.
- Saul Greenberg and Chester Fitchett. Phidgets: Easy Development of Physical Interfaces Through Physical Widgets. In *UIST '01: Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology*, pages 209–218, New York, NY, USA, 2001. ACM Press.
- Christian Guggenmos. Towards a Wearable Snowboarding Assistant. Master's thesis, Department of Computer Science, RWTH Aachen University, December 2007.
- Eric Gunther, Glorianna Davenport, and Sole O'Modhrain. Cutaneous Grooves: Composing for the Sense of Touch. In *NIME '02: Proceedings of the 2002 Conference on New Interfaces for Musical Expression*, pages 37–42, Singapore, Singapore, 2002. National University of Singapore.
- H. Julia Hannay, P. J. Ciaccia, Joan W. Kerr, and Darlene Barrett. Self-report of right-left confusion in college men and women. *Perceptual and Motor Skills*, 70(2):451–457, 1990.
- Jason William Harding, Colin Gordon Mackintosh, David Thomas Martin, Allan Geoffrey Hahn, and Daniel Arthur James. Automated scoring for elite half-pipe snowboard competition: important sporting development or techno distraction? *Sports Technology*, 1(6):277–290, 2009.
- Chris Harrison and Scott E. Hudson. Texture Displays: A Passive Approach to Tactile Presentation. In *CHI '09: Proceedings of the 27th International Conference on Human Factors in Computing Systems*, pages 2261–2264, New York, NY, USA, 2009. ACM Press.
- Björn Hartmann, Scott R. Klemmer, Michael Bernstein, Leith Abdulla, Brandon Burr, Avi Robinson-Mosher, and Jennifer Gee. Reflective Physical Prototyping Through Integrated Design, Test, and Analysis. In *UIST '06: Proceedings of the 19th annual ACM Symposium on User Interface Software and Technology*, pages 299–308, New York, NY, USA, 2006. ACM Press.
- Björn Hartmann, Leith Abdulla, Manas Mittal, and Scott R. Klemmer. Authoring Sensor-based Interactions by Demonstration with Direct Manipulation and Pattern Recognition. In *CHI '07: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 145–154, New York, NY, USA, 2007. ACM Press.

- Vincent Hayward and Juan M. Cruz-Hernández. Tactile display device using distributed lateral skin stretch. In *IMECE'00: Proceedings of the 8th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 1309–1314. IEEE, 2000.
- Thomas T. Hewett, Ronald Baecker, Stuart Card, Tom Carey, Jean Gasen, Marilyn Mantei, Gary Perlman, Gary Strong, and William Verplank. *ACM SIGCHI Curricula for Human-Computer Interaction*. ACM Press, New York, 1992.
- Anke Hilgers. Towards a Tactile Language for Movement Instructions. Master's thesis, Department of Computer Science, RWTH Aachen University, October 2008.
- Cristy Ho, Hong Z. Tan, and Charles Spence. Using spatial vibrotactile cues to direct visual attention in driving scenes. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(6):397–412, 2005.
- Hochschulsport der RWTH Aachen, 2007. URL <http://hochschulsport.rwth-aachen.de>.
- Alexander Hoffmann, Daniel Spelmezan, and Jan Borchers. TypeRight: a Keyboard with Tactile Error Prevention. In *CHI '09: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2265–2268, New York, NY, USA, April 2009. ACM Press.
- Eve Hoggan, Stephen A. Brewster, and Jody Johnston. Investigating the Effectiveness of Tactile Feedback for Mobile Touchscreens. In *CHI '08: Proceeding of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1573–1582, New York, NY, USA, 2008. ACM Press.
- Eve Hoggan, Andrew Crossan, Stephen A. Brewster, and Topi Kaaresoja. Audio or Tactile Feedback: Which Modality When? In *CHI '09: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2253–2256, New York, NY, USA, 2009. ACM Press.
- Maureen K. Holden. Virtual Environments for Motor Rehabilitation: Review. *Cyberpsychology & Behavior*, 8(3):187–211, 2005.
- Kevin Huang, Thad Starner, Ellen Do, Gil Weiberg, Daniel Kohlsdorf, Claas Ahlrichs, and Ruediger Leibrandt. Mobile Music Touch: Mobile Tactile Stimulation for Passive Learning. In *CHI '10: Proceedings of the 28th International Conference on Human Factors in Computing Systems*, pages 791–800, New York, NY, USA, 2010. ACM Press.
- Immersion Corporation. Immersion Studio, 2010a. URL <http://www.immersion.com/>.
- Immersion Corporation. VibeTonz, 2010b. URL <http://www.vibetonz.com>.
- Infusion Systems, 2007. URL <http://infusionsystems.com/>.

- Stephen S. Intille, Ling Bao, Emmanuel M. Tapia, and John Rondoni. Acquiring In Situ Training Data for Context-Aware Ubiquitous Computing Applications. In *CHI '04: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1–8, New York, NY, USA, 2004. ACM Press.
- Mareike Jacobs. Design and Recognition of Tactile Feedback Patterns for Snowboarding. Master's thesis, Department of Computer Science, RWTH Aachen University, October 2008.
- Daniel A. James, Neil Davey, and Tony Rice. An Accelerometer Based Sensor Platform for Insitu Elite Athlete Performance Analysis. In *Proceedings of the IEEE Conference on Sensors*, pages 1373–1376. IEEE, October 2004.
- Chris Jansen, Arjen Oving, and Hendrik-Jan van Veen. Vibrotactile movement initiation. In *Proceedings of the EuroHaptics International Conference*, pages 110–117, 2004.
- Markus Jonas. Tactile Editor: A Prototyping Tool to Design and Test Vibrotactile Patterns. Master's thesis, Department of Computer Science, RWTH Aachen University, May 2008.
- Lynette A. Jones, Mealani Nakamura, and Brett Lockyer. Development of a Tactile Vest. In *HAPTICS '04: Proceedings of the 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 82–89. IEEE, 2004.
- Lynette A. Jones, Brett Lockyer, and Erin Piatieski. Tactile display and vibrotactile pattern recognition on the torso. *Advanced Robotics*, 20(12): 1359–1374, 2006.
- Lynette A. Jones, Jacquelyn Kunkel, and Edgar Torres. Tactile Vocabulary for Tactile Displays. In *WHC '07: Proceedings of the Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 574–575, Washington, DC, USA, 2007. IEEE Computer Society.
- Emil Jovanov, Aleksandar Milenković, Chris Otto, and Piet C. de Groen. A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 2(6):1–10, 2005.
- Holger Junker, Paul Lukowicz, and Gerhard Tröster. PadNET: Wearable Physical Activity Detection Network. In *ISWC '03: Proceedings of the 7th IEEE International Symposium on Wearable Computers*, pages 244–245, Washington, DC, USA, 2003. IEEE Computer Society.
- Holger Junker, Paul Lukowicz, and Gerhard Tröster. Locomotion Analysis Using a Simple Feature Derived from Force Sensitive Resistors. In *BioMED '06: Proceedings of the 2nd International Conference on Biomedical Engineering*, pages 6–9. Acta Press, 2004.

- Kurt A. Kaczmarek, John G. Webster, Paul Bach y Rita, and Willis J. Tompkins. Electrotactile and Vibrotactile Displays for Sensory Substitution Systems. *IEEE Transactions on Biomedical Engineering*, 38(1): 1–16, 1991.
- Kevin S. C. Kuang, Wesley J. Cantwell, and Patricia J. Scully. An evaluation of a novel plastic optical fibre sensor for axial strain and bend measurements. *Measurement Science and Technology*, 13(10):1523–1534, 2002.
- Kai Kunze, Michael Barry, Ernst Heinz, Paul Lukowicz, Dennis Majoe, and Juerg Gutknecht. Towards Recognizing Tai Chi – An Initial Experiment Using Wearable Sensors. In *IFAWC '06: Proceedings of the 3rd International Forum on Applied Wearable Computing*, April 2006.
- Martin Kusserow, Oliver Amft, and Gerhard Tröster. BodyANT: Miniature wireless sensors for naturalistic monitoring of daily activity. In *BodyNets '09: Proceedings of the 4th International Conference on Body Area Networks*, LNICST. ICST, April 2009.
- Doo Young Kwon and Markus Gross. Combining Body Sensors and Visual Sensors for Motion Tracking. In *ACE '05: Proceedings of the International Conference on Advances in Computer Entertainment Technology*, pages 94–101, New York, NY, USA, 2005. ACM Press.
- Henry A. Landsberger. *Hawthorne Revisited*. Cornell University, 1968.
- Jeff Lieberman and Cynthia Breazeal. TIKL: Development of a Wearable Vibrotactile Feedback Suit for Improved Human Motor Learning. *IEEE Transactions on Robotics*, 23(5):919–926, 2007.
- Robert W. Lindeman and Justin R. Cutler. Controller Design for a Wearable, Near-Field Haptic Display. In *HAPTICS '03: Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 397–403, Washington, DC, USA, 2003. IEEE Computer Society.
- Robert W. Lindeman, Robert Page, Yasuyuki Yanagida, and John L. Sibert. Towards Full-Body Haptic Feedback: The Design and Deployment of a Spatialized Vibrotactile Feedback System. In *VRST '04: Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, pages 146–149, New York, NY, USA, 2004a. ACM Press.
- Robert W. Lindeman, John L. Sibert, Corinna E. Lathan, and Jack M. Vice. The Design and Deployment of a Wearable Vibrotactile Feedback System. In *ISWC '04: Proceedings of the 8th IEEE International Symposium on Wearable Computers*, pages 56–59, Washington, DC, USA, 2004b. IEEE Computer Society.
- Robert W. Lindeman, Yasuyuki Yanagida, Kenichi Hosaka, and Shinji Abe. The TactaPack: A Wireless Sensor/Actuator Package for Physical Therapy Applications. In *VR '06: Proceedings of the IEEE Virtual Reality Conference*, pages 337–341, Washington, DC, USA, March 2006a. IEEE Computer Society.

- Robert W. Lindeman, Yasuyuki Yanagida, Haruo Noma, and Kenichi Hosaka. Wearable vibrotactile systems for virtual contact and information display. *Virtual Reality*, 9(2–3):203–213, 2006b.
- Logitech. Logitech Force 3D Pro, 2010. URL <http://www.logitech.com/>.
- Rui C. V. Loureiro, C. F. Collin, and W. S. Harwin. Robot aided therapy: challenges ahead for upper limb stroke rehabilitation. In *ICDVRAT'04: Proceedings of the 5th International Conference on Disability, Virtual Reality and Associated Technologies*, pages 11–14, UK, 2004. University of Reading.
- Joseph Luk, Jerome Pasquero, Shannon Little, Karon MacLean, Vincent Levesque, and Vincent Hayward. A Role for Haptics in Mobile Interaction: Initial Design Using a Handheld Tactile Display Prototype. In *CHI '06: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 171–180, New York, NY, USA, 2006. ACM Press.
- Paul Lukowicz, Holger Junker, Matthias Stäger, Thomas von Büren, and Gerhard Tröster. WearNET: A Distributed Multi-Sensor System for Context Aware Wearables. In Gaetano Borriello and Lars Erik Holmquist, editors, *UbiComp 2002: Proceedings of the 4th International Conference on Ubiquitous Computing*, volume 2498 of *LNCS*, pages 361–370, London, UK, 2002. Springer-Verlag.
- Paul Lukowicz, Tünde Kirstein, and Gerhard Tröster. Wearable Systems for Health Care Applications. *Methods of Information in Medicine*, 43(3):232–238, 2004.
- Paul Lukowicz, Andreas Timm-Giel, Michael Lawo, and Otthein Herzog. WearIT@work: Toward Real-World Industrial Wearable Computing. *IEEE Pervasive Computing*, 6(4):8–13, 2007.
- Karon MacLean and Mario Enriquez. Perceptual Design of Haptic Icons. In *Proceedings of the EuroHaptics International Conference*, pages 351–363, 2003.
- Diane M. Maddox, Gabriele Wulf, and David L. Wright. The effect of an internal vs. external focus of attention on the learning of a tennis stroke. *Journal of Exercise Psychology*, 21, 1999.
- Makingthings. Make Controller Kit, 2010. URL <http://makingthings.com/>.
- Steve Mann. Smart Clothing: The Shift to Wearable Computing. *Communications of the ACM*, 39(8):23–24, 1996.
- Thomas Martin, Emil Jovanov, and Dejan Raskovic. Issues in Wearable Computing for Medical Monitoring Applications: A Case Study of a Wearable ECG Monitoring Device. In *ISWC '00: Proceedings of the 4th IEEE International Symposium on Wearable Computers*, pages 43–48, Washington, DC, USA, 2000. IEEE Computer Society.

- Corinne Mattmann, Oliver Amft, Holger Harms, Gerhard Tröster, and Frank Clemens. Recognizing Upper Body Postures using Textile Strain Sensors. In *ISWC '07: Proceedings of the IEEE International Symposium on Wearable Computers*, pages 1–8. IEEE Computer Society, 2007.
- Measurand Inc. ShapeWrap III, 2010. URL <http://www.measurand.com/>.
- Florian Michahelles and Bernt Schiele. Sensing and Monitoring Professional Skiers. *IEEE Pervasive Computing*, 4(3):40–46, 2005.
- Bruce J. P. Mortimer, Gary A. Zets, and Roger W. Cholewiak. Vibrotactile transduction and transducers. *The Journal of the Acoustical Society of America*, 121(5):2970–2977, 2007.
- Florian 'Floyd' Mueller, Frank Vetere, Martin R. Gibbs, Jesper Kjeldskov, Sonja Pedell, and Steve Howard. Hug Over A Distance. In *CHI '05: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1673–1676, New York, NY, USA, 2005. ACM Press.
- Brad Myers, Scott E. Hudson, and Randy Pausch. Past, Present, and Future of User Interface Software Tools. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 7(1):3–28, 2000.
- Akio Nakamura, Sou Tabata, Tomoya Ueda, Shinichiro Kiyofuji, and Yoshinori Kuno. Dance Training System with Active Vibro-Devices and a Mobile Image Display. *IROS '05: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3075–3080, 2005.
- Nintendo. Nintendo Wii Balance Board, 2010. URL <http://www.nintendo.com/wii/what/accessories/balanceboard>.
- Masataka Niwa, Yasuyuki Yanagida, Huraio Noma, Kenichi Hosaka, and Yuichiro Kume. Vibrotactile Apparent Movement by DC Motors and Voice-coil Tactors. In *ICAT '04: Proceedings of the 14th International Conference on Artificial Reality and Telexistence*, pages 126–131, 2004.
- NOAD2. *The New Oxford American Dictionary*. Oxford University Press, 2nd edition, May 2005.
- Ian Oakley, Marilyn Rose McGee, Stephen Brewster, and Philip Gray. Putting the Feel in 'Look and Feel'. In *CHI '00: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 415–422, New York, NY, USA, 2000. ACM Press.
- R. Ohmura, F. Naya, H. Noma, and K. Kogure. B-Pack: A Bluetooth-based Wearable Sensing Device for Nursing Activity Recognition. In *ISWPC'06: 1st International Symposium on Wireless Pervasive Computing*. IEEE Communications Society, 2006.
- Österreichischer Skiverband (ÖSV), 2009. URL <http://www.oesv.at/>.
- Joseph A. Paradiso, Stacy J. Morris, Ari Y. Benbasat, and Erik Asmussen. Interactive Therapy with Instrumented Footwear. In *CHI '04: Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1341–1343, New York, NY, USA, 2004. ACM Press.

- Jin-Hoon Park, Charles H. Shea, and David L. Wright. Reduced-frequency concurrent and terminal feedback: A test of the guidance hypothesis. *Journal of motor behavior*, 32(3):287–296, September 2000. ISSN 0022-2895.
- Alex Pentland. Healthwear: Medical Technology Becomes Wearable. *Computer*, 37(5):42–49, May 2004.
- Gerald Pirkel, Karl Stockinger, Kai Kunze, and Paul Lukowicz. Adapting Magnetic Resonant Coupling Based Relative Positioning Technology for Wearable Activity Recognition. In *ISWC '08: Proceedings of 12th IEEE International Symposium on Wearable Computers*, pages 47–54, Piscataway, September 2008. IEEE Computer Society.
- Joseph Polastre, Robert Szewczyk, and David Culler. Telos: Enabling Ultra-Low Power Wireless Research. In *IPSN '05: Proceedings of the 4th International Symposium on Information Processing in Sensor Networks*, pages 364–369, Piscataway, NJ, USA, 2005. IEEE Press.
- Ivan Poupyrev, Shigeaki Maruyama, and Jun Rekimoto. Ambient Touch: Designing Tactile Interfaces for Handheld Devices. In *UIST '02: Proceedings of the 15th annual ACM Symposium on User Interface Software and Technology*, pages 51–60, New York, NY, USA, 2002. ACM Press.
- Attila A. Priplata, James B. Niemi, Jason D. Harry, Lewis A. Lipsitz, and James J. Collins. Vibrating insoles and balance control in elderly people. *The Lancet*, 362(9390):1123–1124, 2003.
- Python Software Foundation. Python, 1991. URL <http://www.python.org/>.
- Lawrence R. Rabiner. A Tutorial on Hidden Markov Models and Selected Applications in Speech Recognition. *Proceedings of the IEEE*, 77(2):257–286, 1989.
- Charlotte M. Reed, William M. Rabinowitz, Nathaniel I. Durlach, Louis D. Braida, S. Conway-Fithian, and M. C. Schultz. Research on the Tadoma method of speech communication. *The Journal of the Acoustical Society of America*, 77(1):247–257, 1985.
- Bradley J. Rhodes. The wearable remembrance agent: a system for augmented memory. In *ISWC '97: Proceedings of the 1st IEEE International Symposium on Wearable Computers*, pages 123–128. IEEE Computer Society Press, 1997.
- Monty Roberts. *The Man Who Listens to Horses*. Random House, 1997.
- David A. Ross and Bruce B. Blasch. Wearable Interfaces for Orientation and Wayfinding. In *ASSETS '00: Proceedings of the 4th International ACM Conference on Assistive Technologies*, pages 193–200, New York, NY, USA, 2000. ACM Press.
- Martin Rothenberg, Ronald T. Verrillo, Stephen A. Zahorian, Michael L. Brachman, and Jr. Stanley J. Bolanowski. Vibrotactile frequency for

- encoding a speech parameter. *The Journal of the Acoustical Society of America*, 62:1003–1012, 1977.
- A. F. Rovers and H. A. van Essen. HIM: A Framework for Haptic Instant Messaging. In *CHI '04: Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1313–1316, New York, NY, USA, 2004. ACM Press.
- Grzegorz Rozenberg and Arto Salomaa. *Handbook of Formal Languages, Vol. 1–3*. Springer, Berlin, 1997.
- Angus H. Rupert. An Instrumentation Solution for Reducing Spatial Disorientation Mishaps. *IEEE Engineering in Medicine and Biology*, 19: 71–80, 2000.
- Katri Salminen, Veikko Surakka, Jani Lylykangas, Jukka Raisamo, Rami Saarinen, Roope Raisamo, Jussi Rantala, and Grigori Evreinov. Emotional and Behavioral Responses to Haptic Stimulation. In *CHI '08: Proceeding of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1555–1562, New York, NY, USA, 2008. ACM.
- Alan W. Salmoni, Richard A. Schmidt, and Charles B. Walter. Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin*, 95(3):355–386, 1984.
- SAMH Engineering Services. Shake SK7, 2010. URL <http://code.google.com/p/shake-drivers/>.
- Adalbert Schanowski. A Mobile Sensor/Actuator Platform for Real-Time Mistake Detection and its Application to Snowboarding. Master's thesis, Department of Computer Science, RWTH Aachen University, May 2008.
- Sinon Schätzle, Thomas Hulin, Carsten Preusche, and Gerd Hirziner. Evaluation of Vibrotactile Feedback to the Human Arm. In *Proceedings of the EuroHaptics International Conference*, pages 557–560, 2006.
- Robert Scheibe, Mathias Moehring, and Bernd Froehlich. Tactile Feedback at the Finger Tips for Improved Direct Interaction in Immersive Environments. In *3DUI'07: Proceedings of the IEEE Symposium on 3D User Interfaces*, pages 125–132. IEEE Computer Society, 2007.
- William Schiff and Emerson Foulke. *Tactual perception: A sourcebook*. Cambridge University Press, 1982.
- Albrecht Schmidt and Kristof Van Laerhoven. How to Build Smart Appliances. *IEEE Personal Communications*, 8(4):66–71, August 2001.
- Albrecht Schmidt, Michael Beigl, and Hans-Werner Gellersen. There is more to Context than Location. *Computers & Graphics*, 23(6):893–901, 1999.
- Richard A. Schmidt. Frequent augmented feedback can degrade learning: Evidence and interpretations. *Tutorials in Motor Neuroscience*, pages 59–75, 1991.

- Michael Schrage. Cultures of Prototyping. In *Bringing Design to Software*, pages 191–213. Addison-Wesley, 1996.
- SensAble Technologies, Inc. Phantom Omni Haptic Device, 2010. URL <http://www.sensable.com/haptic-phantom-omni.htm>.
- Charles H. Shea and Gabriele Wulf. Enhancing motor learning through external-focus instructions and feedback. *Human Movement Science*, 18(4):553–571, 1999.
- Carl E. Sherrick. Studies of apparent tactual movement. In Dan R. Kenshalo, editor, *The Skin Senses*, pages 331–345. Springfield, Ill.: Charles C. Thomas, 1968a.
- Carl E. Sherrick. Bilateral apparent haptic movement. *Perception & Psychophysics*, 4(3):159–162, 1968b.
- Carl E. Sherrick. A scale for rate of tactual vibration. *The Journal of the Acoustical Society of America*, 78(1):78–83, 1985.
- Carl E. Sherrick and James C. Craig. The psychophysics of touch. In William Schiff and Emerson Foulke, editors, *Tactual perception: A sourcebook*, pages 55–81. Cambridge University Press, 1982.
- John Simpson and Edmund Weiner. *The Oxford English Dictionary*. Oxford University Press, 2nd edition, 2009. URL <http://www.oed.com/>.
- Aaron E. Sklar and Nadine B. Sarter. Good Vibrations: Tactile Feedback in Support of Attention Allocation and Human-Automation Coordination in Event-Driven Domains. *Human Factors*, 41(4):543–552, 1999.
- Asim Smailagic and Dan Siewiorek. User-Centered Interdisciplinary Design of Wearable Computers. *SIGMOBILE Mobile Computing and Communications Review*, 3(3):43–52, July 1999.
- Asim Smailagic, Dan P. Siewiorek, Richard Martin, and John Stivoric. Very Rapid Prototyping of Wearable Computers: A Case Study of Custom versus Off-the-Shelf Design Methodologies. In *DAC '97: Proceedings of the 34th Conference on Design Automation Conference*, pages 315–320, New York, 1997. ACM Press.
- SNOW SPORT Team, 2007. URL <http://www.sportarten.rwth-aachen.de/SkiAG/joomla/>.
- SnowWorld Landgraaf, 2007. URL <http://www.snowworld.com/>.
- Sonic Golf. Sonic Golf Club, 2008. URL <http://www.sonicgolf.com/>.
- Daniel Spelmezan and Jan Borchers. Real-time Snowboard Training System. In *CHI '08: Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3327–3332, New York, NY, USA, April 2008. ACM Press.
- Daniel Spelmezan, Adalbert Schanowski, and Jan Borchers. Rapid Prototyping for Wearable Computing. In *ISWC '08: Proceedings of 12th IEEE International Symposium on Wearable Computers*, pages 109–110, Washington, DC, USA, September 2008. IEEE Computer Society.

- Daniel Spelmezan, Anke Hilgers, and Jan Borchers. A Language of Tactile Motion Instructions. In *MobileHCI '09: Proceedings of the 11th International Conference on Human Computer Interaction with Mobile Devices and Services*, pages 218–221, New York, NY, USA, September 2009a. ACM Press.
- Daniel Spelmezan, Mareike Jacobs, Anke Hilgers, and Jan Borchers. Tactile Motion Instructions for Physical Activities. In *CHI '09: Proceedings of the 27th International Conference on Human Factors in Computing Systems*, pages 2243–2252, New York, NY, USA, April 2009b. ACM Press.
- Daniel Spelmezan, Adalbert Schanowski, and Jan Borchers. Wearable Automatic Feedback Devices for Physical Activities. In *BodyNets '09: Proceedings of the 4th International Conference on Body Area Networks*, pages 1–8, Brussels, Belgium, Belgium, April 2009c. ICST.
- Vince Stanford. Wearable Computing Goes Live in Industry. *IEEE Pervasive Computing*, 1(4):14–19, October 2002.
- Thad Starner. The Challenges of Wearable Computing: Part 1. *IEEE Micro*, 21(4):44–52, 2001.
- Bonnie G. Steele, Basia Belza, Kevin Cain, Catherine Warms, Jeff Copper-smith, and JoEllen Howard. Bodies in motion: Monitoring daily activity and exercise with motion sensors in people with chronic pulmonary disease. *Journal of Rehabilitation Research and Development*, 40(5 Suppl 2):45–58, 2003.
- Robert J. Stone. Haptic Feedback: A Brief History from Telepresence to Virtual Reality. In Stephen A. Brewster and Roderick Murray-Smith, editors, *Proceedings of the 1st International Workshop on Haptic Human-Computer Interaction*, volume 2058 of *LNCS*, pages 1–16. Springer, 2001.
- Ian R. Summers, Craig M. Chanter, Anna L. Southall, and Alan C. Brady. Results from a Tactile Array on the Fingertip. In *Proceedings of the EuroHaptics International Conference*, pages 26–28, 2001.
- Sun Microsystems. Java, 1995. URL <http://www.oracle.com/us/technologies/java>.
- Sun Microsystems. Sun SPOT, 2004. URL <http://www.sunspotworld.com/>.
- Michael Sung, Carl Marci, and Alex Pentland. Wearable feedback systems for rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 2(17), 2005.
- Suunto. Suunto G6, 2009. URL <http://www.suuntocampaigns.com/G6/>.
- Masami Takahata, Kensuke Shiraki, Yutaka Sakane, and Yoichi Takebayashi. Sound Feedback for Powerful Karate Training. In *NIME '04: Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 13–18, Singapore, Singapore, 2004. National University of Singapore.

- Hong Tan, Adrian Lim, and Ryan Traylor. A Psychophysical Study of Sensory Saltation with an Open Response Paradigm. In Satish. S. Nair, editor, *Proceedings of the ASME Dynamic Systems and Control Division*, volume 69–2, pages 1109–1115, 2000.
- Hong Z. Tan and Alex Pentland. Tactual Displays for Wearable Computing. In *ISWC '97: Proceedings of the 1st IEEE International Symposium on Wearable Computers*, pages 84–89, Washington, DC, USA, 1997. IEEE Computer Society.
- Hong Z. Tan, Rob Gray, J. Jay Young, and Ryan Traylor. A Haptic Back Display for Attentional and Directional Cueing. *Haptics-e: The Electronic Journal of Haptics Research*, 3(1), June 2003.
- Emmanuel M. Tapia, , Stephen S. Intille, Louis Lopez, and Kent Larson. The Design of a Portable Kit of Wireless Sensors for Naturalistic Data Collection. In Kenneth P. Fishkin, editor, *PERVASIVE '06: Proceedings of 4th International Conference on Pervasive Computing*, number 3968 in LNCS, pages 117–134, Berlin / Heidelberg, 2006. Springer-Verlag.
- Technology Review. A Training Tool for Athletes, 2008. URL <http://www.technologyreview.com/computing/20546/>.
- Ryan Traylor and Hong Z. Tan. Development of a Wearable Haptic Display for Situation Awareness in Altered-gravity Environment: Some Initial Findings. In *HAPTICS '02: Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 159–164. IEEE Computer Society, 2002.
- Koji Tsukada and Michiaki Yasumura. ActiveBelt: Belt-type Wearable Tactile Display for Directional Navigation. In *UbiComp '04: Proceedings of the 6th International Conference on Ubiquitous Computing*, number 3205 in LNCS, pages 384–399, Berlin / Heidelberg, 2004. Springer-Verlag.
- Jan B. F. van Erp. Guidelines for the Use of Vibro-Tactile Displays in Human Computer Interaction. In *Proceedings of the EuroHaptics International Conference*, pages 18–22, 2002.
- Jan B. F. van Erp. Presenting directions with a vibrotactile torso display. *Ergonomics*, 48(3):302–313, 2005.
- Jan B. F. van Erp and Hendrik A. H. C. van Veen. Vibro-Tactile Information Presentation in Automobiles. In *Proceedings of the EuroHaptics International Conference*, pages 99–104, 2001.
- Jan B. F. van Erp and Hendrik A. H. C. van Veen. A Multipurpose Tactile Vest for Astronauts in the International Space Station. In *Proceedings of the EuroHaptics International Conference*, pages 405–408, Dublin, Ireland, 2003.
- Jan B. F. van Erp, Hendrik A. H. C. van Veen, Chris Jansen, and Trevor Dobbins. Waypoint Navigation with a Vibrotactile Waist Belt. *ACM Transactions on Applied Perception (TAP)*, 2(2):106–117, 2005.

- Jan B. F. Van Erp, Ian Saturday, and Chris Jansen. Application of tactile displays in sports: where to, how and when to move. In *Proceedings of the EuroHaptics International Conference*, pages 90–95, 2006.
- Hendrik A. H. C. van Veen and Jan B. F. van Erp. Tactile Information Presentation in the Cockpit. In *Proceedings of the First International Workshop on Haptic Human-Computer Interaction*, volume 2058 of *LNCS*, pages 174–181, Berlin / Heidelberg, 2001. Springer.
- W. van Winsum. The functional visual field as indicator of workload. In *Proceedings of the meeting of the Dutch ergonomics association*, pages 182–189, 1999.
- Ronald T. Verrillo and Georg A. Gescheider. Perception via the sense of touch. In Ian R. Summers, editor, *Tactile Aids for the Hearing Impaired*, pages 1–36. Whurr Publishers Ltd., London, 1992.
- Daniel Vlastic, Rolf Adelsberger, Giovanni Vannucci, John Barnwell, Markus Gross, Wojciech Matusik, and Jovan Popović. Practical Motion Capture in Everyday Surroundings. In *ACM Transactions on Graphics*, New York, NY, USA, 2007. ACM Press.
- Conrad Wall, Marc S. Weinberg, Patricia B. Schmidt, and David E. Krebs. Balance Prosthesis Based on Micromechanical Sensors Using Vibrotactile Feedback of Tilt. *IEEE Transactions on Biomedical Engineering*, 48(10):1153–1161, 2001.
- Steven A. Wall and Stephen Brewster. Sensory substitution using tactile pin arrays: Human factors, technology and applications. *Signal Processing*, 86(12):3674–3695, 2006.
- Sidney Weinstein. Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In Dan R. Kenshalo, editor, *The Skin Senses*, pages 195–218. Charles C. Thomas, Springfield, Ill., 1968.
- Janet M. Weisenberger and Mary E. Percy. Use of the Tactaid II and Tactaid VII with Children. *Volta Review*, 96(5):41–57, 1994.
- Greg Welch and Eric Foxlin. Motion Tracking: No Silver Bullet, but a Respectable Arsenal. *IEEE Computer Graphics and Applications*, 22(6):24–38, 2002.
- Tracy Westeyn, Helene Brashear, Amin Atrash, and Thad Starner. Georgia Tech Gesture Toolkit: Supporting Experiments in Gesture Recognition. In *ICMI '03: Proceedings of the 5th International Conference on Multimodal Interfaces*, pages 85–92, New York, NY, USA, 2003. ACM Press.
- Gertjan Wijnalda, Steffen Pauws, Fabio Vignoli, and Heiner Stuckenschmidt. A Personalized Music System for Motivation in Sport Performance. *IEEE Pervasive Computing*, 4(3):26–32, 2005.
- John Williamson, Roderick Murray-Smith, and Stephen Hughes. Shoogle: Excitatory Multimodal Interaction on Mobile Devices. In *CHI '07: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 121–124, New York, NY, USA, 2007. ACM Press.

- Carolee J. Winstein. Knowledge of Results and Motor Learning—Implications for Physical Therapy. *Physical Therapy*, 71(2):140–149, February 1991.
- Hendrik Witt, Tom Nicolai, and Nicky Kern. The WUI-Toolkit: A Model-Driven UI Development Framework for Wearable User Interfaces. In *ICDCSW '07: Proceedings of the 27th International Conference on Distributed Computing Systems Workshops*, pages 43–43, Washington, DC, USA, 2007. IEEE Computer Society.
- Gabriele Wulf. *Attention and Motor Skill Learning*. Human Kinetics, 2007. ISBN 073606270X.
- Gabriele Wulf, Nancy McNevin, and Charles H. Shea. The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology*, 54A(4):1143–1154, 2001.
- Gabriele Wulf, Nathan McConnel, Matthias Gärtner, and Andreas Schwarz. Enhancing the Learning of Sport Skills Through External-Focus Feedback. *Journal of Motor Behavior*, 34(2):171–182, 2002.
- Xsens Technologies B.V. MTx and MVN - Inertial Motion Capture, 2010. URL <http://www.xsens.com/>.
- Xing-Dong Yang, Walter F. Bischof, and Pierre Boulanger. Validating the Performance of Haptic Motor Skill Training. In *Proceedings of the 2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 129–135. IEEE Computer Society Washington, DC, USA, 2008.
- Hiroaki Yano, Tetsuro Ogi, and Michitaka Hirose. Development of Haptic Suit for Whole Human Body Using Vibrators. *Transactions of the Virtual Reality Society of Japan*, 3(3):141–148, 1998.
- Andreas Zinnen and Bernt Schiele. A New Approach to Enable Gesture Recognition in Continuous Data Streams. In *ISWC '08: Proceedings of 12th IEEE International Symposium on Wearable Computers*, pages 33–40. IEEE, 2008.

Index

- AA batteries 24, 83
- abstract mapping 67, 77
- accelerometer *see* sensor, accelerometer
- active situation 76, 80, 94, 132
- activity recognition 15, 17, 44, 54
- actuator 19, 24, 62, 207
- inertial 62
 - linear 63
 - piezoelectric 63
 - shape memory alloy 64
- adaptation *see* mechanoreceptors, rate of adaptation
- alphabet 128, 223
- Braille 68, 128
- amplitude *see* encoding parameters, intensity
- ANOVA 97, 136
- apparent movement 66, 117
- Arduino BT 18, 24, 48, 161, 207
- artificial tactile stimuli *see* tactile stimuli
- athlete 1–4, 6, 76, 153
- ATMega168 17, 161
- attentional focus
- external 104, 155, 159
 - internal 155, 159
- augmented feedback *see* feedback, extrinsic
- automatic control processes 155
-
- back foot 36
- backpack 96, 103, 111
- backside edge 36, 41, 44, 47, 159
- backside turn 36, 41, 44, 156
- balance board 94, 130
- basic instructions *see* tactile motion instructions, basic
- basic stance *see* neutral position
- basic turn 37, 130, 157
- BD *see* burst duration
- bend sensor *see* sensor, bend
- between-subjects design 86, 90, 133, 182
- blind experiment 164, 170
- Bluetooth 17, 18, 20, 23, 27, 41
- body movements *see* tactile motion instructions, body movements
- bones 65, 91
- Braille alphabet *see* alphabet, Braille
- burst duration 80
-
- car drivers 70, 80
- carving 50, 166, 167

- circuit schematic.....24, 207
classification of context..... *see* context recognition
coach..... 1–3, 154, 183
coded approach..... 67, 77
cognitive load..... 77, 79, 187
cognitive workload..... 80, 94, 95, 101, 110, 190
compass heading..... 17, 39, 42
compound instructions..... *see* tactile motion instructions, compound
constrained-action hypothesis..... 155
context recognition..... 15, 23, 27
context-aware..... 14, 16, 19, 24
corpuscles..... *see* mechanoreceptors
counter-rotation..... *see* snowboarding, counter-rotation
counterbalanced..... 96, 105, 112, 114, 118, 135, 164
countermovement..... 89, 91
cutaneous rabbit..... *see* sensory saltation
cutaneous sense..... 59
- D-sub connector..... 25
daily physical activities..... *see* physical activities
dancing..... 5, 127, 141
dermis..... 59
design guidelines..... 64, 80, 91, 115, 121, 190
design space..... 77, 188
desktop computer..... 14, 18
direct approach..... *see* pictorial approach
directional cues..... *see* navigation
directional lines..... 66, 80, 86, 91, 121, 190
dorsal..... 82
- Earcons..... 65, 67, 82
earplugs..... 1, 105
edging angle..... 1, 38, 50, 163, 167
electro shock..... 35
emotional communication..... 68, 72
encoding metaphor
- counter-intuitive..... 132, 142
- intuitive..... 132, 142
- mixed..... 136, 146, 147, 149, 151
- push and pull..... 90, 92, 120, 133, 147, 151, 157, 191
encoding parameters..... 64
- body location..... 65, 67
- duration..... 65, 67, 79, 80
- frequency..... 64, 85
- intensity..... 64, 65, 67
- primary..... 67
- rhythm..... 65, 67
- waveform..... 65
environmental audio cues..... 1, 108
epidermis..... 59
equestrienne..... *see* horseback riding
exponential smoothing..... 47, 51
expressive sensations..... 78, 90, 187, 190
external focus..... *see* attentional focus, external
extrinsic frame of reference..... 79
- fakie..... *see* riding switch

- fall line 37, 167
- feedback
- audio 4, 13
 - concurrent 1, 153–156, 159, 181
 - delayed 1, 34, 154
 - extrinsic 154
 - force 5, 62, 72
 - frequent 1, 154, 155
 - immediate 3, 34, 154
 - intrinsic 154
 - tactile 2, 5, 6, 19, 24, 62
 - visual 4, 155, 181
- feedback on performance 1, 154
- feedforward 154, 164
- fitness 4
- force feedback *see* feedback, force
- force sensor *see* sensor, force
- force-sensitive resistor *see* sensor, force
- forced-choice paradigm 118, 133, 146
- front foot 36, 157
- frontside edge 36, 41, 44, 47, 159
- frontside turn 36, 41, 44, 156
- FSR *see* sensor, force
- gesture recognition 15
- goofy *see* stance, goofy
- GoWear fit 4
- Graphical User Interface 29, 129
- GUI *see* Graphical User Interface
- guidance hypothesis 154
- gyroscope *see* sensor, gyroscope
- haptic device *see* feedback, force
- haptic guidance 5
- haptic icons 30, 67, 77, 129
- haptic phonemes *see* haptic icons
- Hawthorne effect 183
- HCI *see* Human-Computer Interaction
- headphones 87, 96, 118, 135, 145
- hearing impaired persons 62, 69, 129
- Hidden Markov Model 15, 19
- horseback riding 110
- Hug Shirt 72
- Human-Computer Interaction 7
- hypodermis 59
- I-CubeX 18
- IBI *see* inter-burst interval
- inertial measurement unit 15, 16
- instructor *see* coach
- inter-burst interval 80
- interactive throwing sleeve 4
- internal focus *see* attentional focus, internal
- interviews with snowboard instructors 34, 43
- intrinsic frame of reference 79
- intuitive *see* tactile motion instructions, intuitive interpretation
- iSense 28

- iterative design 20
- Java 18, 27
- kinesthetic sense 62
- knee pads 38
- knee-jerk reaction *see* reflex action
- knowledge of performance 154
- knowledge of results 154
- language
 - formal 128, 223
 - spoken 127
 - tactile 69, 127
- lateral 82
- Latin alphabet 223
- left-right confusion 101, 131, 143
- letters 128, 223
- Likert scale 107, 113, 174
- localized pulses *see* localized stimuli
- localized stimuli 75, 78, 80, 88
- low-pass filter *see* exponential smoothing
- lumbago 6
- Mac OS X 27
- machine learning 15
- magnetometer *see* sensor, magnetometer
- martial arts 4, 17
- masking effects 67
- mean shifting 47, 51
- mechanoreceptors 60
 - frequency range 61
 - Meissner's corpuscles 60
 - Merkel's discs 60
 - Pacinian corpuscles 60
 - rate of adaptation 61, 67
 - receptive field 61
 - receptor density 61
 - Ruffini's corpuscles 60
 - spatial resolution 61
- medial 82
- Meissner's corpuscles *see* mechanoreceptors, Meissner's corpuscles
- Merkel's discs *see* mechanoreceptors, Merkel's discs
- metaphorical approach 68
- micro-controller 17, 161
- misinterpretation *see* tactile motion instructions, misinterpretation
- mobile device
 - interaction 71
 - Nokia N70 27, 40, 103, 111, 160
- Morse code 128
- motion capture suit, MVN 16
- motion model 3, 54
- motion recognition 15
- motion tracker, MTx 16
- motor *see* vibration motor
- Motor Control 27
- motor shield 24, 45, 207
- motor skill learning 1, 5, 154

- motor skills
 - closed 155
 - open 155, 156
- movement initiation 75
- moving average 47, 52
- muscles 79

- natural audio cues *see* environmental audio cues
- navigation 69, 70, 75, 79, 80, 130
- neutral position 36, 40, 46
- Nike + iPod 4
- Nintendo Wii Fit *see* balance board
- noisy environment 1
- Nokia 3270 *see* vibration motor, Nokia 3270
- Nokia N70 *see* mobile device, Nokia N70
- notation *see* tactile patterns, notation

- obstacle detection 71
- open response paradigm 86, 146
- Optacon 67, 68
- optical bend sensor *see* sensor, optical bend
- Optohapt 69, 129

- Pacinian corpuscles *see* mechanoreceptors, Pacinian corpuscles
- parabolic flights 80
- patient 5, 6, 13
- pause *see* inter-burst interval
- personal digital assistant 14
- personal training device 4
- physical activities 2–4, 6, 76, 127
- physical computing 18
- physical user interface 18
- physically and cognitively demanding 76, 94
- piano playing *see* 5
- pictorial approach 67
- piezoelectric effect 63
- piezoresistive bend sensor *see* sensor, bend
- pilots 70, 80
- pivoting 37, 167
- posture model 3, 54
- posture recognition 15
- pouch 40, 45, 160
- pressure sensation *see* tactile sense
- pressure sensor *see* sensor, force
- privacy 71
- proactive 14
- programming by demonstration 19, 199
- prototyping 20, 23
 - platform 18
- pull metaphor *see* encoding metaphor, pull
- pulse 69, 78, 82
- pulse width modulation 20, 24, 85, 207
- push metaphor *see* encoding metaphor, push
- pushing and pulling sensations 2, 75, 77, 90
- PWM *see* pulse width modulation
- Python 27, 103, 160

- rabbit *see* sensory saltation

-
- rapid feedback system 4
 - real-world conditions 102, 110, 153
 - real-world sensations 77, 90, 187
 - receptors *see* mechanoreceptors
 - reference values 40, 46, 47, 50, 51
 - reflex action 75, 145, 187
 - regular *see* stance, regular
 - rehabilitation 5, 76
 - repeated-measures design *see* within-subjects design
 - response time 106, 109
 - riding at trot *see* riding gaits
 - riding at walk *see* riding gaits
 - riding gaits 112, 114
 - riding switch 157
 - roughness *see* encoding parameters, waveform
 - Ruffini's corpuscles *see* mechanoreceptors, Ruffini's corpuscles

 - sampling rate 40, 46, 161
 - semicircular lines 116, 120
 - SensAct box 24, 45, 160
 - SensAct Control 29, 30
 - sensing device 16, 23
 - sensor 3
 - accelerometer 4, 15, 54, 85
 - bend 15, 38
 - force 39, 45, 160, 163
 - gyroscope 15
 - magnetometer 16
 - optical bend 45, 54
 - stretch 15
 - Sensor Monitor 27
 - sensory saltation 66, 69, 79, 80, 117
 - sensory substitution 68
 - sequence of body movements 127, 130
 - Shake SK6 17, 19, 39
 - Shapiro-Wilk test 171
 - SIGCHI *see* Special Interest Group in Human-Computer Interaction
 - sine wave 63, 65, 83
 - single instructions *see* tactile motion instructions, basic
 - Ski Coach 4
 - skiing 4, 17
 - skin 59
 - SMA *see* moving average
 - smart clothes 2
 - snowboard training system *see* wearable snowboarding assistant
 - snowboarding 1, 94, 102, 153
 - activity recognition 54
 - classification of riding edge 46, 166
 - context information 44
 - counter-rotation 38, 157, 170
 - course 159
 - knee flexion 38, 42, 51
 - mistakes 34, 36, 157, 170
 - terminology 36
 - wrong weight distribution 38, 157, 170
 - SnowSport Team 34, 43, 159, 170
 - SnowWorld Landgraaf 38, 46, 104, 159

- solenoid 63, 71
 Sonic Golf Club 4
 spatially separated 1, 72
 spatiotemporal pattern 29, 66
 Special Interest Group in Human-Computer Interaction 7
 speech recognition 15
 spine and sternum 115, 121
 spoken instructions 1, 103, 109
 spoken language *see* language, spoken
 sports competitions 13
 sports training 1–4, 6, 75, 154
 square wave 65, 83
 stabilometer platform 155
 stance
 - goofy 36, 159
 - regular 36, 159
 stationary situation 80, 94, 116, 132
 stiff posture 34, 38
 stretch sensor *see* sensor, stretch
 Suunto G6 4
 switch *see* riding switch

 TactaBoard 20
 TactaBox 20
 Tactaid 69, 129
 TactaPack 20
 tactile display
 - device 19, 23
 - technologies 62
 Tactile Editor 29
 tactile feedback *see* feedback, tactile
 tactile feedback device *see* tactile display, device
 tactile icons *see* Tactons
 tactile instructions *see* tactile motion instructions
 tactile language *see* language, tactile
 tactile motion instructions 2, 75
 - basic 131
 - body location 81
 - body movements 91, 144, 184
 - compound 130, 157, 162, 191
 - design recommendations 91, 115, 121, 190
 - design requirements 77, 187
 - duration 80, 162, 191
 - final set 184
 - intuitive interpretation 86, 144
 - learning time 145
 - misinterpretation 97, 101, 110, 114, 131, 151
 - patterns 91, 116, 121, 184
 - primary encoding parameter 115, 121, 191
 - secondary encoding parameter 115, 121, 191
 - upper body rotation 89, 116
 tactile patterns
 - compound 83, 89
 - design 29
 - notation 82
 - one-element 82
 - rotation 79

- simultaneous83, 89
- tactile sense 60
- tactile signals *see* tactile stimuli
- tactile stimuli2, 5, 30, 75
- tactile suit 83
- tactile vest 20
- Tactons 67, 77, 82, 129
- tactor *see* actuator
- Tadoma 129
- tap 75, 80
- tennis 1, 155
- textual information transfer68, 128
- threshold test 15, 41, 47, 50, 52, 55, 163
- timing values 80, 86, 162
- toolkit 16
- TRS connector 24, 45
- TS connector 24
- two-point threshold 61, 65, 82
- typing errors 71

- unsupervised situations 6, 76

- ventral 82
- verbal instructions *see* spoken instructions
- verbal responses 95, 101, 106, 109, 110, 114, 132, 141, 143, 151
- Vibratase 69, 77, 129
- vibration motor 2, 24, 62, 83
 - cylindrical 62, 83
 - frequency 85
 - intensity 85, 108, 160
 - Nokia 3270 83
 - pancake 62
- vibration sensation *see* tactile sense
- Vibrocons 70
- vibrotactile 62, 84
- video analysis 28, 40, 46, 170
- virtual reality 72, 78
- visual phi phenomenon *see* apparent movement
- visually impaired persons 68, 129

- waist belt 70
- warning signals 70, 71, 80
- wearable assistant 2
- wearable computing 2, 6, 13
- wearable sensing and feedback device 2, 16, 23
- wearable snowboarding assistant 7, 33, 44, 153
- Wii Fit *see* balance board
- Wilcoxon signed-rank test 108, 119, 170, 171, 174
- window size 47, 50, 52
- within-subjects design 96, 105, 164
- words 127, 130, 223
- workload *see* cognitive workload
- wrong posture 2, 36
- wrong upper body rotation *see* snowboarding, counter-rotation
- wrong weight distribution *see* snowboarding, wrong weight distribution

- young adults 76, 80, 90, 154, 184

Publications

Daniel Spelmezan, Anke Hilgers, and Jan Borchers. A Language of Tactile Motion Instructions. In *MobileHCI '09: Proceedings of the International Conference on Human-Computer Interaction with Mobile Devices and Services*, pages 218–221, New York, NY, USA, September 2009. ACM Press.

Daniel Spelmezan, Mareike Jacobs, Anke Hilgers, and Jan Borchers. Tactile Motion Instructions for Physical Activities. In *CHI '09: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2243–2252, New York, NY, USA, April 2009. ACM Press.

Alexander Hoffmann, Daniel Spelmezan, and Jan Borchers. TypeRight: a Keyboard with Tactile Error Prevention. In *CHI '09: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2265–2268, New York, NY, USA, April 2009. ACM Press.

Daniel Spelmezan, Adalbert Schanowski, and Jan Borchers. Wearable Automatic Feedback Devices for Physical Activities. In *BodyNets '09: Proceedings of the International Conference on Body Area Networks*, pages 1–8, Brussels, Belgium, Belgium, April 2009. ICST.

Daniel Spelmezan, Adalbert Schanowski, and Jan Borchers. Rapid Prototyping for Wearable Computing. In *ISWC '08: Proceedings of IEEE International Symposium on Wearable Computers*, pages 109–110, Washington, DC, USA, September 2008. IEEE Computer Society.

Daniel Spelmezan and Jan Borchers. Real-time Snowboard Training System. In *CHI '08: Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3327–3332, New York, NY, USA, April 2008. ACM Press.

Daniel Spelmezan and Jan Borchers. Minnesang: Speak Medieval German. In *CHI '06: Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1355–1360, New York, NY, USA, April 2006. ACM Press.

Curriculum Vitae

Personal Data

Daniel Spelmezan

13. August 1976

Born in Bistrița, Romania
Nationality German

1987 – 1996

Grotenbach Gymnasium Gummersbach
Gummersbach, Germany
Abitur

1997 – 2003

RWTH Aachen University
Aachen, Germany
Diploma in Computer Science (Dipl.-Inform.)

2004

RWTH Aachen University
Aachen, Germany
Start of Doctorate in Computer Science

