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Dissertation

COMPUTER-SUPPORTED ASSISTIVE SYSTEMS FOR IN-SITU MOVEMENT GUIDANCE IN SPORTS

by
Felix Kosmalla (M.Sc.)
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Reporters:	Prof. Dr. Antonio Krüger
	Prof. Michael Jones, PhD
Examination Board Chair:	Prof. Dr. Verena Wolf
Scientific Assistant:	Dr. Florian Daiber

Notes on style:

The work presented in this dissertation is in many cases the result of collaborations with other students and researchers. We therefore use the scientific plural "we" to reflect the efforts of all parties involved. References to scientific resources are provided in the Bibliography chapter, with the use of DOIs where available. Online resources are referred to using URLs. All URLs have been last accessed on January 20, 2025. Where necessary, they have been shortened to enhance readability and formatting. The style and typeset of this document is based on the typographical look-and-feel of "classicthesis v4.6", referenced in the Colophon.

ABSTRACT

Sports have evolved from a means of preparing for hunting or battle to an established component of modern physical fitness and recreation. Regardless of the level of professionalism, correct movement techniques are essential to enhance performance and to reduce the risk of injuries. Traditional autodidactic training methods to learn those techniques, such as books or videos, rely on the trainees understanding of the principles conveyed and their ability to implement them independently. Personal trainers bridge this gap by delivering tailored guidance. However, their accessibility is limited. To address these challenges, computer-supported assistive systems have emerged as a promising addition, providing context-dependent feedback during movement execution. This thesis contributes to future design, implementation, and invesitgation of those systems by presenting several artifacts and accompanying studies, specifically for real-time feedback in rock-climbing and slacklining. Firstly, we implement and study a computer-supported slackling training assistant that teaches novices to walk on a slackline by means of automatic instructions and real-time feedback during the exercise. We show that the system can serve as an effective method for autonomously learning the basics of slackline training. Next, we investigate the perception of different notification channels during a rock climbing ascent. We show that audible and vibro-tactile feedback prove effective for delivering real-time notifications during climbing while visual notifications emerging from the wrist are unsuitable. Following this, we investigate different visualization approaches for real-time expert modelling in rock climbing. We find that none of the visualization techniques excell in every aspect of guiding through a movement by itself. Instead, we propose a hybrid approach that combines the strengths of each technique while minimizing their weaknesses. Finally, we introduce two systems designed to enable future research in computer-supported assistive systems for sports. The first is a toolkit for rapid prototyping of smart insoles, using low-cost pressure sensors and microcontrollers to support the development of sensing applications for foot-related feedback. This is followed by a platform for creating mixed reality climbing experiences on physical rock climbing walls and climbing treadmills. We argue that these technologies allow for the design of flexible, controlled research environments where technology induced constraints or physical limitations in real-world setups can be mitigated.

ZUSAMMENFASSUNG

Sport hat sich im Laufe der Zeit von einem Mittel zur Vorbereitung auf die Jagd oder den Kampf zu einem festen Bestandteil der modernen körperlichen Fitness und Freizeitgestaltung entwickelt. Unabhängig von dem Niveau, auf dem der Sport betrieben wird, sind korrekte Bewegungstechniken für die Verbesserung der Leistung und die Verringerung des Verletzungsrisikos unerlässlich. Klassische autodidaktische Trainingsmethoden zum Erlernen dieser Techniken, wie Bücher oder Videos, setzen voraus, dass die Trainierenden die vermittelten Prinzipien vollständig verstehen und selbstständig umsetzen können. Persönliche Trainer schließen diese Lücke, indem sie maßgeschneidertes Feedback geben, sind jedoch nicht immer verfügbar. Um diese Herausforderungen zu adressieren, haben sich computergestützte Assistenzsysteme als vielversprechende Ergänzung herauskristallisiert, die ein an den Sportkontext angepasstes Feedback während der Bewegungen liefern. Die vorliegende Arbeit leistet einen Beitrag zur Gestaltung, Implementierung und Erprobung solcher Systeme, indem sie mehrere Systeme und begleitende Studien im Kontext Echtzeit-Feedback beim Klettern und Slacklinen vorstellt. Zunächst implementieren und untersuchen wir einen computergestützten Slackline-Trainingsassistenten, der Anfängern das Gehen auf einer Slackline mittels Echtzeit-Feedback während der Übung beibringt. Eine begleitende Nutzerstudie zeigt, dass das System eine effektive Methode zum autonomen Erlernen der Grundlagen des Slackline-Trainings darstellt. Darauf folgend untersuchen wir die Wahrnehmung verschiedener Modalitäten für Notifikationen während des Kletterns. Es zeigt sich, dass akustisches und vibrotaktiles Feedback eine geeignete Modalität ist, während sich visuelle Benachrichtigungen am Handgelenk als ungeeignet erwiesen haben. Anschließend untersuchen wir verschiedene Visualisierungsansätze, in denen Trainierende die Bewegungen von virtuellen Experten nachahmen sollen. Aus den Ergebnissen leiten wir ab, dass keine der Visualisierungstechniken für sich genommen in allen Aspekten der Bewegungsführung überlegen ist. Alternativ schlagen wir einen hybriden Ansatz vor, der die Stärken der einzelnen Techniken kombiniert und ihre Schwächen minimiert. Abschließend stellen wir zwei Systeme vor, die zukünftige Forschung im Bereich computergestützter Assistenzsysteme für den Sport ermöglichen sollen. Das erste System ist ein Toolkit für das Entwerfen schneller Prototypen-Designs von intelligenten Einlegesohlen, das kostengünstige Drucksensoren und Mikrocontroller verwendet, um die Entwicklung von Sensoranwendungen für Feedback zur Fußtechnik zu unterstützen. Das zweite System stellt eine Plattform für die Entwicklung von Mixed-Reality-Klettererlebnissen an physischen Kletterwänden und Kletterlaufbändern dar. Durch dieses System wird die Gestaltung flexibler, kontrollierter Forschungsumgebungen ermöglicht, in denen technologiebedingte Einschränkungen oder physische Beschränkungen in realen Umgebungen aufgehoben werden können.

PUBLICATIONS

In the following, we provide a chronological list of publications that form the basis of this thesis. They are supplemented by descriptions of the individual contributions of authors and collaborators. Where applicable, we indicated the names of those collaborators, that are no co-authors, typically students and research assistants with a "(*)".

FULL PAPERS

Felix Kosmalla, Frederik Wiehr, Florian Daiber, Antonio Krüger and Markus Löchtefeld. "Climbaware: Investigating Perception and Acceptance of Wearables in Rock Climbing". *In: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems.* CHI'16, USA [133]

Ideation & Conceptualization	Felix Kosmalla & all
Online Study	
Design	Felix Kosmalla & all
Implementation	Felix Kosmalla
Analysis	Felix Kosmalla
Perception Study	
Design	Felix Kosmalla & all
Hardware Implementation	Felix Kosmalla
Software Implementation	Frederik Wiehr
Execution	Felix Kosmalla & Frederik Wiehr
Analysis	Felix Kosmalla & Frederik Wiehr
Feedback & Review:	Florian Daiber & Antonio Krüger & Markus Löchtefeld

Felix Kosmalla, Florian Daiber, Frederik Wiehr and Antonio Krüger.
"Climbvis: Investigating in-situ visualizations for understanding climbing movements by demonstration".
In: Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces. ISS'17, USA [130]

Ideation & Conceptualization:	Felix Kosmalla & Florian Daiber
Perception Study:	
Design:	Felix Kosmalla & Florian Daiber
Implementation:	Felix Kosmalla (Augmented Third-Person-Views)
	Frederik Wiehr (Life-Size Projection)
Execution:	Felix Kosmalla
Analysis:	Felix Kosmalla & Florian Daiber
Feedback & Review:	Frederik Wiehr & Antonio Krüger

Felix Kosmalla, Christian Murlowski, Florian Daiber and Antonio Krüger.
"Slackliner - An Interactive Slackline Training Assistant".
In: Proceedings of the 26th ACM international conference on Multimedia. MULTIMEDIA'18, Republic of Korea. [131]

Ideation & Conceptualization:	Felix Kosmalla, Florian Daiber, Christian Murlowski
Study:	
Design:	Felix Kosmalla, Florian Daiber, Christian Murlowski
Implementation,	Christian Murlowski under
Execution & Analysis:	the guidance of Felix Kosmalla
Feedback & Review:	Florian Daiber & Antonio Krüger

LATE BREAKING WORKS, WORKSHOP PAPERS & TUTORIALS

Felix Kosmalla, Frederik Wiehr, Florian Daiber, Antonio Krüger. "Using Off-the-shelf Sensors for Ad-hoc Smart Sole Prototyping". *In: Proceedings of the ACM UbiComp Workshop on Ubiquitous Computing in the Mountains (UbiMount).* UBICOMP'16, Germany [132]

Ideation & Conceptualization:	Felix Kosmalla & Frederik Wiehr
Implementation:	
Hardware:	Felix Kosmalla
Software:	Frederik Wiehr
Feedback & Review:	Florian Daiber & Antonio Krüger

Florian Daiber, **Felix Kosmalla**. "Tutorial on Wearable Computing in Sports". *In: Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services.* MobileHCI'17, Austria [42]

Ideation & Conceptualization:	Felix Kosmalla & Florian Daiber
Concept and Implementation of Hands-On:	Felix Kosmalla
Feedback & Review:	Florian Daiber & Antonio Krüger

Felix Kosmalla, André Zenner, Marco Speicher, Florian Daiber, Nico Herbig, Antonio Krüger. "Exploring Rock Climbing in Mixed Reality Environments". *In: Extended Abstracts of the 2017 CHI Conference on Human Factors in Computing Systems* CHI'17, USA [134]

Ideation & Conceptualization:	Felix Kosmalla & André Zenner
Framing in the Context of Virtual Reality:	André Zenner & Marco Speicher
Implementation:	Felix Kosmalla & André Zenner
Feedback & Review:	Florian Daiber & Nico Herbig & Antonio Krüger

Felix Kosmalla, André Zenner, Corinna Tasch, Florian Daiber, Antonio Krüger. "The Importance of Virtual Hands and Feet for Virtual Reality Climbing". *In: Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* CHI'20, Virtual [135]

Ideation & Conceptualization:	Felix Kosmalla & André Zenner & Corinna Tasch
Study *(not presented in this thesis)*:	
Design	Felix Kosmalla & André Zenner & Corinna Tasch
Implementation, Execution & Analysis:	Corinna Tasch under the guidance of Felix Kosmalla
Feedback & Review:	Florian Daiber & Antonio Krüger

Felix Kosmalla, Florian Daiber, Antonio Krüger. "InfinityWall–Vertical Locomotion in Virtual Reality using a Rock Climbing Treadmill." *In: Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* CHI'22, USA [129]

Ideation & Conceptualization:	Felix Kosmalla
Implementation:	
VR Climbing System:	Felix Kosmalla
Wall Editor:	Jan Ehrlich* & Philip Hell* under the guidance of Felix Kosmalla
Feedback & Review:	Florian Daiber & Antonio Krüger

The author of this dissertation has supervised a total of eight Bachelor's theses and five Master's theses, many of which are in the context of sports and human-computer interaction. Two Bachelor's theses are still ongoing at the time of submission of this dissertation. In addition to the publications mentioned above, the author has contributed to several other works at the intersection of human-computer interaction in sports and related fields. Beyond publications, the author has also contributed to the organization of four workshops and one tutorial in this domain.

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I am deeply grateful to everyone who supported me on this journey, which began several years ago. To all of you, I express my sincere gratitude, even if I inadvertently fail to mention you by name.

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In addition to the colleagues mentioned above, I am also deeply grateful to the student research assistants and those who chose me as their advisor for their theses, some of which contributed to parts of this work. Thank you, (in alphabetical order), **Jan Ehrlich**, **Felix Philipp Felten**, **Philip Hell**, **Lena Hornberger**, **Fabian Hupperich**, **Christian Murlowski** who became a member of the lab, **Leon Sauerwald**, and **Corinna Tasch**.

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Last, but most importantly, I thank my fantastic partner **Kim**. Thank you for your endless patience, encouragement, support, and love, which you continue to give me.

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ACRONYMS

UD Ultimate Display

UAS Ultimate Assistive System

STM short-term memory

LTM long-term memory

WM working memory

KR Knowledge of Results

KP Knowledge of Performance

AR Augmented Reality

MR Mixed Reality

VR Virtual Reality

RV Reality-Virtuality

HCI Human Computer Interaction

HMD Head Mounted Display

IMU Inertial Measurement Unit

GPIO General-Purpose Input/Output

BLE Bluetooth Low Energy

FSR Force-Sensing Resistor

CAD Computer Aided Design

SLA Slackline Training System

HUM Human Trainer

Part I

INTRODUCTION

1

PROLOGUE

Figure 1.1: The forests of Fontainebleau house the biggest, developed bouldering area in the world. Climbers from all over the world come to enjoy the intricate bouldering problems that are offered by the sandstone formations. Here, a climber is tackling a bouldering problem, with a spotter providing support and crash pads for safety.

After a 40-minute train ride from Paris, you arrive in the small city of Fontainebleau. Here, in its woods, nestled within pine and birch trees, a vastness of sandstone can be found. Large boulders of various forms and shapes are bedded on fine sand, attracting climbers from all over the world. Equipped with only climbing shoes and bulky portable mats, so-called crashpads, enthusiasts have made it their goal to scale these boulders. The ascent of these boulders pose individual challenges, known as "problems", to be solved. To prevent serious injury in the event of an unexpected fall, the crashpads are placed on the base of the boulder to cushion the climber.

In the late spring of 2013, I visited *Bleau* for the first time. The day started with strolling around the boulders surrounded by fragrant pine trees, looking for the next climbing problem to solve. Having recently purchased new climbing shoes and at that time being in quite good form, I felt prepared to conquer these boulders. After achieving some minor successes during warm-up, I decided to challenge myself with a more complex ascent but failed miserably early on.

Later on that day at the same place, an elderly gentleman appeared on the scene. I would have placed him in his late seventies. He wore climbing shoes that could not have looked more different to mine, exhibiting the wear and tear of countless ascents. With a leisurely pace, he approached the same boulder I failed to scale. Instead of a crashpad, he placed down an old piece of carpet, wiped his shoes, and applied some *Pof*, a resin obtained from pines, used to regulate respiration on the hands. Then, he began his ascent. I could not believe my eyes, as he moved with a lightness that can only have come from years of practice and experience. It seemed like his body became one with the rock face as he scaled the boulder's surface, carefully placing his feet on tiny ledges, shifting his body weight, and using the friction of his hands, grabbing onto the stone where no obvious hold could be seen, to finally reach its summit. This gentleman's performance was a revelation. It became very clear that his successful ascent was not solely dependent on gear or physical strength but on the mastery honed over many years in the forests of Fontainebleau.

This particular scene embodies the core motivation behind my thesis. From an early age on, I have always been fascinated by technology that reacts to the movements of the human body. This started with kids' shoes that would light up with every step taken and continued with commodity hardware like the Microsoft Kinect that would allow you to control a computer game with your whole body. Eventually, the increased accessibility of various sensors and microcontrollers allowed me to tinker with these technologies on a much lower level. Suddenly, it was possible to quickly build small systems like a wrist-worn gadget that would light up when you shook your arm. While this particular example does not display a significant purpose, it shows the potential that technology has to assist a human in real-time in doing something based on the movement that is being performed at the very moment, at the very place.

Now, given the scene from Fontainebleau above, what if we could design and build systems that would ultimately help in mastering movements such as the climbing skills displayed by the older gentleman? Instead of depending on a human personal trainer, who might not always be available for reasons of temporal, spatial or financial constraints, such assistive systems would empower every individual, regardless of age, physical condition, or skill level, to excel in their chosen sport. These systems would offer guidance, monitor performance, and provide feedback similar to a personal trainer. They would transform any space into a personalized training ground, accessible anytime and anywhere. With this thesis, I aim to contribute to this ultimate goal.

2 INTRODUCTION

Sports have played a crucial role throughout history. Early on, sports were mainly used for preparing for the hunt or battle, while today promoting physical fitness and bringing people together plays a more important role [39]. One example of the latter is one of the oldest sporting events that is still relevant today: the Olympic Games. The first recording dates back to 775 BC [68], when the travel to the playing grounds was a strenuous endeavor by itself. As opposed to the early beginnings, where the aspects of battle training could be found in disciplines like a race in armor in 520 BC [246], today's Olympics are adapted to the modern world. While track and field are still a manifested component of the Olympic Games, new sports have been introduced since the beginning of the games, with some of the newest additions being skateboarding, windsurfing, or sports climbing in 2020. Regardless of the discipline, the Olympic Games are one of the most competitive global competitions where participants train and evolve their techniques to be the best in the world.

Not only within the realm of the Olympic Games but also in general, sports have continually evolved and adapted to the changing dynamics of society. Today, people integrate sports into their everyday lives in different manifestations. Some enjoy sports as *visitors* to sporting events. Others partake in these sporting events as *professional athletes*. They pursue a career in sports, abiding by a rigorous training schedule. Their training progress and schedule are often supervised by a *trainer or coach* who gives personalized instructions on how to optimize the training and technique of the athlete. *Hobbyists* on the other hand participate in sports primarily for personal enjoyment, recreation, or to stay fit. Depending on the intrinsic motivation of the hobbyist, the intensity in which they conduct their training varies greatly. People who enjoy the recreational aspect of sports might just go on the occasional jog along the river while others lend training methods of professional athletes and apply them to their workout regimen.

With this solidified integration of sports in today's society, its importance also rose. For instance, in the United States, sports scholarships offer students who excel in their sports opportunities to attend prestigious universities, without the need to fund their college tuition by themselves. Sports also play an important role as a catalyst for the development of life skills, transferring skills learned during practicing sports to non-sport settings [84]. Regular physical activity has also been shown to be beneficial for physical fitness, health, and overall psychological well-being [78]. Engaging in these activities helps individuals build and maintain a strong, resilient body, contributing to cardiovascular health, improving heart function and circulation, and reducing the risk of chronic diseases like obesity, diabetes, and hypertension [2, 169].

Despite the variety of sports one can pursue, improving one's skills allows every athlete - whether a hobbyist or professional - to excel in performance. While intuitively this seems only relevant for professional athletes whose careers depend on their accomplishments, improving one's skills is beneficial for athletes of every level in many different ways. It helps the sportsperson to use less power while running, to move with more elegance on a slackline, to hold a rock climbing grip a little longer, or simply but importantly to reduce the risk of serious injuries.

2.1 HOW PEOPLE LEARN SPORTS

There is an abundance of possibilities to learn these techniques, some being more accessible than others. Autodidactic methods like books and videos allow the trainees to move at their own pace, drawing from the knowledge of experts in a certain field. This method, however, is reliant on the fact that the trainees have to understand the principles conveyed in the book by themselves. Wrongly applied techniques might not be obvious to the trainee but might result in incorrect progress as well as wrongly acquired skills or, in the worst case, injuries. This might stem from the difficulty of translating theoretical knowledge from books into practical skills without hands-on practice.

Videos may mitigate some of these drawbacks. Movements can be communicated more clearly, by showing them from different angles, split into submovements, or replayed in slow-motion. However, one crucial drawback remains: both books and videos cannot deliver feedback instantly during the activity (**real-time**) and directly within the actual context or environment of the sport **(in-situ)**, which may eventually lead to the development of incorrect habits that are challenging to correct later on. One opportunity to gain more in-depth, hands-on practice, and feedback is to train with a group, be it an official training of a sports club or privately organized meetups. For example in sports like rock climbing or slacklining, it is common to share knowledge and tips during an exercise session. Having someone give small tips like shifting one's weight to a different foot can make the difference between scaling the top or falling on the padded mat below the climbing wall. The one-to-many characteristic of group training can reduce the financial cost of a training session by distributing it among the participants. Conversely, this also divides the amount of time and attention a trainer can spend with a single participant.

Having the benefit of the undivided attention of a trainer enhances the effectiveness immensely. A personal trainer can guide the trainees through several different sessions, correct their movements, and monitor their physical progress. This can be seen as the gold standard of training. However, having a personal trainer giving such personalized care is, with some exemptions such as tennis or golf, reserved for more serious athletes. The reasons for that are varied.

Besides the cost of a personal trainer that was mentioned above, other constraints such as time or geographical limitations might stand in the way of an individual taking private lessons. Being employed full-time only allows for a narrow timespan before or after work to meet up with a trainer. Since this is a problem that is faced by a large proportion of the population, the demand for personal trainers within these timespans will be high, thus complicating the coordination of schedules of both the trainer and the trainee. This might also result in inconsistency in training. Due to the unavailability of a trainer, the trainee's regular schedule cannot be followed, thus resulting in a disruption of training routines. A related problem evolves out of geographical limitations. Depending on the location of the trainee, it might be hard to find qualified personal trainers with the necessary expertise, especially in remote or underserved areas. This becomes particularly challenging when the sport of interest belongs to a niche such as archery or more uncommon martial arts like *Hwa Rang Do* [142] from Korea.

Addressing these challenges, recent research has introduced computer systems that should alleviate the scarcity of trainer resources. These assistive systems are tailored to a specific sport or movement and help the user to improve their technique or learn a certain movement. This is achieved by giving direct, concrete feedback to the user or by augmenting the senses to increase awareness of their own body or surroundings. Examples are systems that are capable of guiding the swing of a golf club [62], learning a dance movement in front of a mirror [10], or augmenting the perception of a snowboarder [177]. While there are already a variety of systems that aim at a specific sport or even a distinct technique (see Section 3.2 for an overview), there is no single overarching, ultimate solution for computer-assisted movement learning yet.

2.2 TOWARDS THE ULTIMATE ASSISTIVE SYSTEM

This raises the question of what capabilities such an interactive system would be required to qualify as the Ultimate Assistive System (UAS), regardless of the current technological limitations in meeting all these criteria. An answer to a similar question was given 1965 by Evan E Sutherland [216] when he introduced his vision of the Ultimate Display (UD). His vision describes the ultimate display as a room in which a computer could control the existence of matter, essentially being able to render anything imaginable, even bullets that would pierce the skin. To this day, Sutherland's vision is a source of inspiration for virtual reality systems such as the CAVE [40] or today's head-mounted displays.

Both being an ideal conception without fully realized implementations, the UD and the UAS share fundamental characteristics. The purpose of the UAS is to support athletes in learning a movement by providing them with optimal feedback at the ideal moment. To deliver this, the UAS would have to possess a variety of capabilities. Primarily, it would need to sense and understand the athlete's actions. Similar to the UD, the UAS would be able to sense the human body in all its facets, including all muscle contractions as well as eye gaze. Its sensing capabilities would span large-scale movements like moving multiple muscles in the upper body during a golf swing but also fine-grained details like the pressure distribution on the golfer's sole of the foot. With a holistic understanding of the athlete's body and its movements, the system would be capable of understanding what the athlete is doing right or wrong. It would be able to adapt in real-time to the athlete's movement and might even foresee them. This would enable the ultimate assistive system to generate ideal movement models that fit perfectly the current individual needs of the athlete.

Ultimately, the system would be able to effectively communicate instructions for improving a movement to the athlete. It would adapt the information conveyed to the athlete's current state of mind and would choose the perfect amount of information, the ideal moment when to convey this information, as well as an appropriate feedback channel. Similar to the UD, the UAS would be able to present anything in any imaginable form, even forces applied to the body, nudging the athlete into the right movement.

Finally, the UAS would preserve the athlete's autonomy. When used by athletes, it would become ubiquitous and integrate seamlessly into their training routine. As a result, neither the athletes nor their surroundings would notice the system when not needed. It would only make itself noticeable when an intervention is necessary to guide the athlete into the right movement. Ultimately, it would not distract the athletes while performing their exercise, increasing the willingness to use such a system.

While it is questionable when and if the UAS could be implemented in its completeness, some aspects can already be addressed with today's technology and methods.

2.3 RESEARCH QUESTIONS

With the works presented in this thesis, we want to investigate factors that are relevant when developing computer-supported assistive systems for sports that are both effective but also accepted by its users. For this, we formulated three main research questions that approach this challenge from three different perspectives (see Table 2.1).

RQ 1 What are factors influencing the acceptance and willingness of athletes to use a computer-supported assistive system for sports training?

The technology acceptance model of Davis [45] proclaims that when presented with a new technology, a future user's decision of how and when they would use such a technology is dependent on perceived usefulness and the perceived ease-of-use. Similar approaches on technology acceptance and usage specific for the sports context have been investigated in the past [19, 171, 221] without specifically focussing on real-time, in-situ feedback for movement guidance. These studies underline the importance of designing systems that align with user needs and expectations. For computer-supported assistive systems, a critical attribute is their unobtrusiveness — allowing them to seamlessly integrate into training without distracting or hindering the athlete as little as possible [161]. While this is hard to achieve at its fullest, considering these aspects should remain important during design, development and evaluation of those systems. In **RQ 1**, we explore factors that influence the acceptance and willingness of athletes to use computer-supported assistive systems for sports training that are employed on- and off-body. We do this by conducting online surveys before the design process and evaluate those aspects in subsequent user studies.

RQ 2 What are effective methods for tracking and assessing movements to inform real-time feedback development and testing in a sports context?

The computer-supported assistive system being developed should provide feedback to athletes based on their movements. This requires the system to maintain a digital model of the athlete's current body state, updated continuously using a combination of sensors and software systems. Building on established methods and technologies, this research question explores how existing tools can be adapted and extended to investigate real-time feedback systems To address this challenge, we instrumented both the athletes and their environment. With this, we aim to inform future explorations and designs of real-time feedback systems, not limited to the sports investigated to this thesis.

RQ 3 How could computer-supported assistive systems communicate feedback and instructions to athletes during training?

Having a model of the current state of the user's body, a computer-supported assistive system can determine how the movements of the user needs to be adapted to follow an optimal movement. To convey this information, the system must employ communication methods that are both appropriate and effective, enabling the athlete to understand and implement the necessary adjustments. The effectiveness of these communication methods depends on several factors, such as fatigue [52] or cognitive load [192]. **RQ 3** approaches this question in the context of rock climbing and slacklining. It investigates how assistive systems can employ various communication methods to guide athletes effectively. This includes exploring different communication channels that target the visual, auditory, and haptic senses of the athlete. Additionally, future research directions for VR-based systems are proposed to investigate novel feedback methods that extend beyond what is physically possible in the real world.

2.4 METHODOLOGY

In this thesis, we implemented a set of different artifacts and systems. To investigate the research questions stated above, we evaluated these artifacts and systems by employing different research practices. With a focus on the user, we conducted most of our research

No.	Research Question	Chapter
RQ 1	What are factors influencing the acceptance and willingness of athletes to use a computer-supported assistive system for sports training?	Chapters 4, 5, 6
RQ 2	What are effective methods for tracking and assessing movements to inform real-time feedback development and testing in a sports context?	Chapters 4, 7
RQ 3	How could computer-supported assistive systems communicate feedback and instructions to athletes during training?	Chapters 4, 5, 6, 8

Table 2.1: Summary of the research questions addressed in this thesis

during field studies when possible. This allowed us to gather real-world data and granted the participants the possibility to use our prototypes in a realistic environment. For some artifacts, we conducted online studies to determine user needs and requirements before implementing a prototype. This included simple questionnaires but also more elaborate online tools that allowed for the collection of more specific data points like the acceptance of body positions for body-worn technology. During the experiments, we collected quantitative data drawn from sensors and coded video recordings. Semi-structured interviews complemented our qualitative data collection.

This approach allowed us to gather empirical evidence, validate our systems, and gain valuable user perspectives.

2.5 CONTRIBUTIONS

This thesis contributes building blocks that enable the implementation and investigation of present and future real-time feedback methods. We do this by contributing empirical studies investigating the prototypes of the presented assistive systems as well as technical systems and platforms.

EMPIRICAL CONTRIBUTIONS The artifacts and systems presented in this thesis were used to conduct several studies investigating how people perceive certain on- and off-body feedback channels during complex movements. In Chapter 4 we present a study of an interactive slackline trainer system. After completing the system-guided training, all participants were able to walk on a slackline. Semi-structured interviews indicated that the game character and the challenging exercises provided by the system motivated the participants to reach their goal of accomplishing the exercises. In Chapter 5 we present a study investigating how well climbers perceive visual, auditive, and haptic cues during ascents of climbing routes differing in difficulty. We found that both audible and vibrotactile feedback are suited for ambient, on-body notifications during climbing. Finally, in Chapter 6 we set the focus on feedback through visualized climbing movements while actively climbing using projections and augmented reality. One of our key findings was that none of the visual feedback methods can provide an overall solution for in-situ video feedback by themselves. Instead, we proposed a hybrid approach that combines the benefits of both, the life-size projection and projected displays.

The results from the studies presented in this thesis give insights into how people perceive certain on- and off-body feedback channels during complex movements.

TECHNICAL CONTRIBUTIONS During the development of the artifacts presented in this thesis, we introduced software and hardware tools that can be used to investigate domains going beyond the initially intended sports. In Chapter 5 we present a novel interface for assessing subjective attributes of body positions by participants that allows the participants to assess the estimated perception of visual, auditive, or haptic cues as well as the willingness to use body-worn devices on a specific body part. While this interface was initially intended to assess suitable body positions during rock-climbing it can be easily adapted and tailored for different sports. Further, we contribute several methods in how to easily prototype sensing mechanisms, that allow for implementing prototypes of assistive systems to study certain aspects of feedback. The Insole Toolkit allows for wireless, ad-hoc prototyping of foot-related sensing applications such as running style or foot placement while climbing, available online (see Chapter 7). In Chapter 4, we show how the Kinect Gesture System can easily be used to implement interactive systems that give qualitative feedback, which is also applicable for other sports or rehabilitation purposes. Finally, in Chapter 8 we propose a virtual reality rock climbing system that allows to climb on physical climbing walls, both static and rotating, while being immersed in a virtual environment by wearing a Head Mounted Display (HMD). All proposed systems are aimed at enabling future research in novel real-time feedback methods.

2.6 OVERVIEW

This thesis is structured as follows. Chapter 3 introduces and discusses the background and related work that are relevant to this work. We introduce basic concepts of how human memory and the movement learning process has been modeled in the past and frame the focus of this thesis' artifacts in Section 3.1. Then, in Section 3.2, we will give an overview of feedback systems for movement learning and motivate the need for further investigation of feedback systems in the sports considered in this thesis: Rock climbing and Slacklining. An overview about these sports, their origins, how these sports are practiced today, and how past research has considered these sports in a Human Computer Interaction (HCI) context is given in Section 3.3. We end the chapter with an overview about past Human Comptuer Interaction research in the context of both fields, opening up the floor for opportunities for assistive systems. This is followed by multiple chapters presenting the core contributions of this thesis (see Table 2.2). Finally, Chapter 9 summarizes the thesis with a conclusion that consolidates the answers to the research questions out of the works presented and discusses limitations and potential future work.

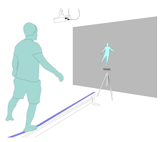
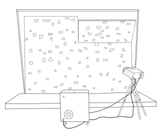
Artifact	Description	Focus	Chapter
	An autonomous training system for slacklining was implemented and evaluated. With the system, novices were able to progress from no slacklining skills over standing on the slackline with one leg to walking from one end to the other. Participants were guided through several exercises by real-time feedback.	Empirical Study & Prototype Development	Chapter 4
	This work focuses on on-body feedback during a rock climbing ascent. Based on an online-study regarding the perceived comfort and perceptiveness of wearable devices, a notification system was implemented. With that, we compared three different output channels - audio, visual, and tactile - during an ascent of a route.	Empirical Study & Prototype Development	Chapter 5
	In this work, the focus was set on augmenting the environment of the athlete. We implemented a setup that allowed a user to simultaneously climb with different visual representations of an expert climber, allowing for continuous guidance during the movement.	Empirical Study & Prototype Development	Chapter 6
	The proposed toolkit introduces a flexible, low-cost foundation for tracking and assessing foot related movements in climbing and other sports using DIY smart insoles.	Prototype Development	Chapter 7
	In an iterative process, we implemented a virtual reality climbing platform that integrates virtual environments with physical climbing walls. We envision future usage scenarios such as for training, rehabilitation, but especially also the exploration of novel feedback methods.	Prototype Development	Chapter 8

Table 2.2: List of the artifacts presented, a short description, methods used, and where to find them in this thesis.

3

BACKGROUND & RELATED WORK

The introduction of computing technology into sports has influenced the way athletes train, learn new skills, and enhance their performance. In the past, these systems were mainly reserved for professional setups, delivering real-time physiological data of the athlete to the trainer which interpreted this data to transform it into meaningful instructions for the athlete. Today, more and more systems are available to the general public, ranging from simple step trackers to sophisticated smartwatches that can analyze a golf swing. Such assistive systems for sports often come in the form of wearable technology or integrated environmental sensors and offer real-time feedback and guidance.

In this chapter, we want to give an overview of the theoretical and practical foundations that form the basis of the use of interactive systems in sports. We begin by briefly discussing how skill in athletes is developed by looking into the working mechanisms of memory and different (motor) learning models. This will allow for the understanding of how athletes acquire and refine new movements. Ultimately, this allows us to identify opportunities throughout the learning process where interactive technologies can be applied.

Following this, we give a broad overview about assistive systems for sports that have been introduced in the past. This section will present different feedback modalities and combinations of them and emphasizes the need to investigate interactive systems in underexplored sports.

Next, we give an introduction to the sports that were used as case studies for the artifacts presented in this thesis: rock climbing and slacklining. We provide background information on how these sports are performed and in which variations the sports are lived. Both sports present unique challenges and demands that require precise movements, balance, and mental focus. Thus, we illustrate why they are particularly interesting as a study object when investigating the use of interactive systems in sports.

Figure 3.1: In the 1960s Erik Kandel started investigating the relatively simple brain of the aplysia californica, a large sea slug. Its brain consists of only 20,000 neurons, which allows for direct investigation of structural change during learning[1].

3.1 SKILL ACQUISITION AND MOTOR LEARNING

As mentioned before, having good form and technique in sports offers several benefits, ranging from enhanced performance to reduced injury risk. Depending on the complexity of movements, achieving proper form and technique typically requires learning. For example, humans naturally learn to walk on their own but to achieve record-breaking sprint times, dedicated learning of techniques is required. This learning process, known as skill acquisition, involves a wide range of cognitive and physical abilities. Within this broader spectrum lies motor learning, a subfield concerned with the processes involved in mastering physical movements.

This section explores how the process of motor learning has been studied in the past to eventually position the work presented in this thesis within the broader context of skill acquisition.

3.1.1 *Motor Learning Theory*

Most aspects of learning take place in the brain, the most complex organ that resides in our body. To study this complex system of neurons and their interconnecting synapses, James Schwarz and Eric Kandel chose a more simplistic study object: the *aplysia californica*, a large sea slug (see Figure 3.1) [117]. While the brain of this slug is constructed much more simply than the one of a human, the circuitry of the only 20,000 neurons of the aplysia allows for the direct observation of change during learning. Kandel's fundamental investigations contributed to later research that explored neurological and psychiatric diseases [77, 189].

1 Picture by Genny Anderson, Licensed under CC BY-SA 4.0, taken from https://tinyurl.com/mb98vuua

However, resulting from the human brain's complexity, there are still open questions and different theories, models, and concepts used to describe and explain individual functions like perception, representation of knowledge, and especially (motor) learning that cannot be answered by looking into a snail's brain.

In the following section, we provide a brief overview of some of the most prominent and widely used concepts, models, and theories in motor learning. First, we define memory, a core component in learning and solidifying new movements or techniques. These learned movements are referred to as motor skills—the ability to coordinate a set of muscles to achieve a specific movement. We will then present a selection of learning models that describe how motor skills are developed before they can be internalized.

3.1.1.1 *Types of Memory*

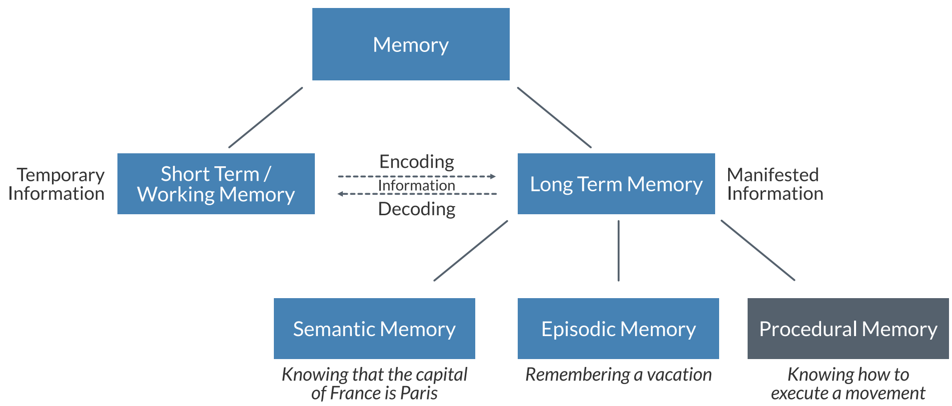


Figure 3.2: Overview of Memory Systems and Their Functions: This graphic illustrates the division of memory into short-term, working, and long-term memory, highlighting key models by Atkinson & Shiffrin and Baddeley et al. It also outlines the categories of long-term memory—semantic, episodic, and procedural—along with the roles of working memory in processing and storing information.

The brain and its functions have fascinated researchers for decades, even centuries, and remain an active area of investigation today — and likely for the foreseeable future. Consequently, an extensive body of research exists, that investigates the cognitive as well as perceptual capabilities of the brain but also the working principles behind memory. However, current textbooks (e.g. [92, 147, 172]) often highlight two concepts of memory: The short-term memory (STM) and long-term memory (LTM) model of Atkinson and Shiffrin [13] as well as the model of Baddeley [16] dividing memory into working-memory and long-term memory. Comparable to short-term, working memory (WM) can temporarily store information that arrived from the senses or has been recalled from long-term memory [27]. Magill [147] summarizes the functions of working memory as a storage space for temporary information but also as a functionally active structure that plays a vital role in problem-solving and especially movement production.

Information that has been processed in WM may eventually transition into LTM. As the name suggests, information that makes it into LTM stay there for days, years, or permanently, only interrupted by periods in which certain memories are temporarily inaccessible due to other incoming information [13]. Tulving [227] divides the knowledge that resides in LTM into three distinct categories: semantic, episodic, and procedural memory. Semantic memory describes knowledge that people possess about the world, for example, knowing that the capital of France is Paris. Episodic memory on the other hands represents personal experiences, such as a memorable visit to a foreign country. Finally, procedural memory is ability knowledge - knowing how to perform a specific task, for example, how to execute a certain movement.

Until a skill is anchored in procedural memory, the person acquiring this skill must undergo a learning process that, among other things, takes place in working memory. This learning step is of particular interest to the systems investigated in this thesis, as these systems are ultimately designed to support the development of procedural memory. The following subsection gives an overview of interpretations of this process in the form of learning models.

3.1.1.2 *Modelling the Acquisition of Motor Skills*

In this thesis, when we discuss *motor skills*, we follow the definition used by Magill [147]: He describes motor skills as "activities or tasks that require voluntary control over movements of the joints and body segments to achieve a goal". Consequently, *motor learning* refers to the acquisition of such motor skills, be it the learning of completely new motor skills, the improvement of already present but not as refined motor skills, or the relearning of motor skills that cannot be performed anymore because of changed circumstances, e.g. after an injury. Down to the present day, there is still a debate on how a new skill is established in the human brain. To explain this process, different models of skill acquisition have been proposed in past research. The most prominent ones that are explained in text books aiming at applying these models in practical settings (e.g. [44, 92, 102, 147, 190]) mostly mention stage-based models. These models assume that the development of a skill is broken down into phases or stages. Each stage represents a different level of proficiency or practice to move from a beginner to a more advanced level of mastery of a certain skill. While the models presented below can be applied to all kinds of skill learning, we describe them in the context of movement learning.

CONSCIOUS COMPETENCE MODEL One of the simpler models is the Conscious Competence Model. It comprises four stages - hence it is also known as the Four Stages of Learning Model [1]. The model's origin cannot be determined to its fullest and has been accredited to various contributors (see [25, 41, 91] as cited by [14]). It describes the progression from not knowing about a skill to performing it effortlessly. In the beginning, the learners are

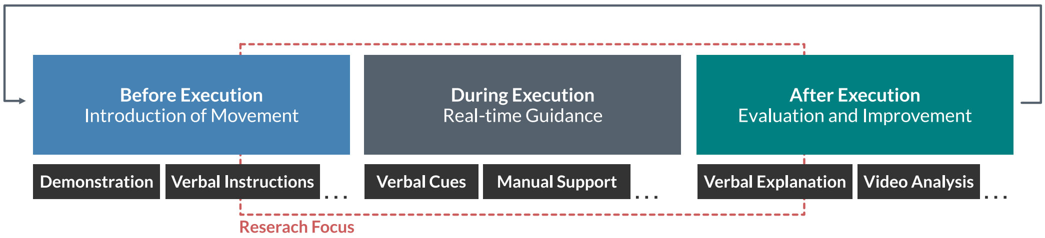


Figure 3.3: Phases of conventional feedback in movement learning: Before Execution (introduction), During Execution (real-time guidance), and After Execution (evaluation and improvement).

unaware of their own unknowingness, also known as *(unconscious incompetence)*. As an example, a child is gifted a bike, although it has never ridden one. After trying and having fallen a couple of times it now knows that it does not know how to ride a bike. The child progressed to the *conscious incompetence* stage - it now knows what it does not know. Given some practice, the child is now able to ride the bike but still has to concentrate to not fall to the ground. This stage, in which the child is aware of its newly acquired ability, is referred to as *conscious competence* stage. Finally, after repetition and practice, routines like pedaling or switching gears become natural while there is still a need to concentrate. The child has now progressed to the *unconscious competence* stage where the whole skill or parts of it come completely naturally without having to think about it. While the Conscious Competence Model explains the way individuals learn, it does not provide measurements that would allow for segregating the individual stages from each other [14].

MODEL OF SKILL ACQUISITION BY FITSS & POSNER The model of skill acquisition defined by Fitts and Posner [69] considers three phases of skill learning. Learners usually gradually shift from one level to another [147]: In the beginning, the learners find themselves in the *Early or Cognitive Phase*. Here, the novices try to understand the task and its requirements, i.e. the attention to cues, events, and responses. Fitts and Posner summarize this phase as the one where instructions and demonstrations are the most effective. Following this, the *Intermediate or Associative Phase* takes place. It describes the manifestation of subroutines learned in the previous phase, i.e. the learner knows how to perform a certain movement. The goal has now shifted from the initial understanding of the movement to refining it [92]. This is now possible since the movements are performed more consistent and the now available cognitive capacities can be used to focus on error detection and correction. The last phase is described as the *Final or Autonomous Phase*. Here, movement execution becomes more and more autonomous and requires less cognitive control and might even allow performing a secondary task [69]. A simple example for this is walking, a well practiced task and talking. During this stage the rate of improvement decreases over time, resulting in a plateauing of skill development. Depending on the skill, to become an expert, the learner has to practice a prolonged period of time, even years [92]. Since the transition through these phases is gradual, it cannot be clearly determined where in which phase a learner is currently in [147].

GENTILE'S TWO-STAGE MODEL OF MOTOR SKILL ACQUISITION In contrast to Fitts & Posners model, Ann Gentile [79] describes the learning process with at least two stages: an *Initial Stage of Learning* and *Fixation / Diversification* Stage (as cited in [147]). In the first stage, similar to the model by Fitts and Posner, the goal is getting an idea of the movement. Here, the novice explores the movement through trial-and error. Especially, the learner needs to understand which cues, such as sensory information from muscles or eyes and ears, are important and which should be ignored [92]. At the end of this phase, the novice is able to produce the movement but cannot do so consistently nor is the movement very efficient [147]. In the Fixation / Diversification, similar to the Associative Phase of Fitts and Posner, the focus lies on increasing the consistency and refinement of the movement [79]. The diversification aspect holds especially for open skills in which, as opposed to a closed skill, the environment may change for each performance of a movement. An example is the learning of hitting a tennis ball that may arrive from a multitude of locations with differing speeds, thus changing the environment for the performance for every try. At the end of the stage, the learner will be able to automatically monitor the environment and modify the movement accordingly [147].

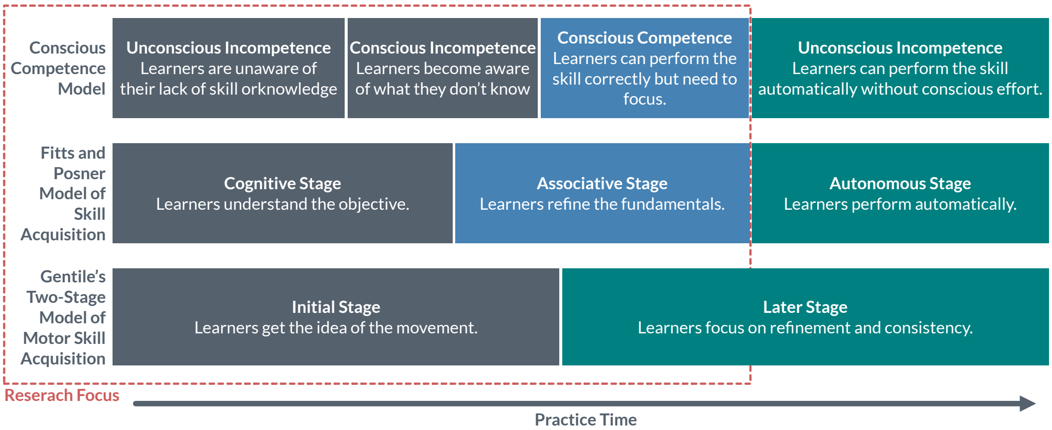


Figure 3.4: Comparison of Skill Acquisition Models: Aligning the Conscious Competence Model, Fitts and Posner's Model of Skill Acquisition, and Gentile's Two-Stage Model to Illustrate the Stages of Learning and Development of Skill

3.1.2 *Motor Learning in the Early Stages*

While the individual stages vary across the models described above, they can be aligned on a scale ranging from novice to expert, as illustrated in Figure 3.4. As shown, the initial understanding and first successful performances happen in the earlier stages. During these stages, the trainees need to align and adapt their movements so that they are closer to the movement to be learned. This alignment can occur by trial and error, but mostly the novice is dependent on feedback. Commonly, feedback is distinguished between intrinsic and extrinsic feedback [200]. Intrinsic feedback is generated from the learners own sensory system giving them information about their internal bodily state and movement or the external environment. The source of extrinsic feedback comes from the outside, e.g. instructions form a trainer, a video recording, a sports watch, or a computerized system [7]. This form of feedback is also referred to as augmented feedback [157]. It adds to the intrinsic feedback of the novice by supplementing it with information that the trainees cannot immediately perceive or know automatically. This includes information about how to shift the bodyweight during a climbing move to reach a specific hold or how to grip the handle of a tennis racket to produce a more forceful or accurate serve. Instructions and feedback can be given at different times during training: before (pre), during (in-situ), or after (post) the performance (see Figure 3.3).

FEEDBACK BEFORE THE EXECUTION When teaching a new movement, one common method is to demonstrate how to perform it correctly before the execution. This method is commonly interchangeably named *modelling* or *observational learning* [92]. In addition to a demonstration which is inherently visual, verbal instructions or cues as well as manual interventions are also often incorporated [102]. An example for a manual or mechanical intervention is the repositioning of body limbs or changing the grasp of sports equipment such as a tennis racket or golf club.

FEEDBACK DURING THE EXECUTION During the performance, a coach may still be able to give feedback to the learner. However, the amount of information that can be conveyed is highly dependent on the task that is performed. For example, a tennis serve is a very quick movement during which an understanding of the verbal (or visual) instruction and a subsequent adaption by the learner might not be feasible. This changes for sports that can be performed slower and where the execution of a movement can be paused, such as in rock climbing. Here, learners can position themselves, listen to the coach, adapt the body position based on the pointing and visual cues, shift some weight and then try to perform the movement. In addition to these contactless cues, a coach could also physically support the movement of the learner during the performance. This method is very common in gymnastics to guide a possible dangerous movement during execution [201]. The idea here is to give the learners an idea how the movement should feel, targeting the proprioception, the sensation and perception of limb position and movement [147] of the learner. Additionally, this form of guidance provides confidence to the learners since they are shown that their body is able to perform the movement [200, 201].

FEEDBACK AFTER THE EXECUTION Another opportunity for a coach to give instructions is after the movement was performed, letting the learners know how they performed. This extrinsic feedback can be categorized in Knowledge of Results (KR) and Knowledge of Performance (KP) [200]. Knowledge of Results includes information for the learners to which degree they performed the movement correctly [239]. On the other hand, Knowledge of Performance includes information in how to adapt in the next trial so that it comes closer to the ideal movement. KR can typically be observed by the learners themselves. For example, putting a golf ball on the green either results in the ball landing in the hole or not. KP on the other hand includes concrete kinematic information such as "your arms were not straight enough during putting", thus the learner is dependent on a coach [200, 235]. As in the feedback given before or during the exercise, post execution feedback can also be given verbally, or enhanced by the replay of a video recording of the trainee. More advanced training facilities may even be equipped with body-worn sensors and optical skeleton tracking systems, both of which provide more detailed information than a standard video recording. However, while these systems offer richer data, the complexity of interpreting such information can pose challenges for both coaches and learners. If not presented in a user-friendly or digestible format, the overwhelming volume and detail of data could confuse the learner, potentially hindering the learning process [83, 224].

3.1.3 *Frequency of Feedback*

External feedback, regardless of the time administered, is a fundamental component in the learning and refinement of motor skills [193]. This additional information can be used by the learners to reflect on past performance as wells as basis for error corrections for the next trial. However, the frequency of this feedback is important. When too little feedback is given, the progression of the learners is slowed down since they cannot identify what to change to improve performance. Giving continuous feedback will develop a dependency of the learner on this feedback (*guidance effect* [8]) ultimately resulting in the inability to detect errors in the execution of movements by themselves [198, 199]. The optimal balance likely lies in a moderate frequency of feedback. In the early stages of motor learning, frequent feedback helps learners to correct gross motor errors and form an initial understanding of the correct movement. During later, more advanced stages, feedback should be reduced to promote the ability of autonomously detecting errors [193, 241]. Finding the right balance of feedback in an ongoing research area. As noted by Haibach et al. [92], no universally optimal feedback reduction schedule has yet been identified.

3.1.4 *Assessing the Learning*

The learning models described above outline the learning process of a novice as a sequence of stages that they undergo. Based on the stage the learner is in, different approaches to feedback and coaching can be applied. This makes it critical to know which stage the learner is currently in. To determine this, the learning progress must be assessed. Depending on the learning stage, different indicators can be utilized, as summarized by [92, 200]. These indicators include characteristics such as performance (to what degree was the goal achieved?), control and coordination (how smooth is the movement?), movement efficiency (how much energy is required for the movement?), and persistence (can the movement still be performed after a long break?). Some of these indicators, such as control, coordination, and efficiency, can be directly measured in a laboratory setting using electromyography (EMG) or inertial measurement units (IMU). However, in most cases, experienced coaches or trainers observe changes in performance based on their expertise.

3.1.5 *Opportunities of Computer-Supported Assistive Systems*

As outlined above, augmented (or external) feedback [157] is especially important in the early stages of learning. Feedback provided at this stage helps learners quickly identify and correct gross errors. This allows them to form an accurate initial understanding of the movement. Traditionally, this feedback is delivered by a trainer who can give feedback in the form of verbal instructions, physical guidance or video demonstrations before, during or after the exercise. However, during the exercise, the amount and form of feedback the trainer can give is limited. This challenge becomes even more complicated during fast or complex movement. Here, the limits of verbal communication and visual observation by the trainee is quickly reached.

Interactive, computerized systems can provide solutions to these challenges. They are capable of sensing the trainees' movement through body-worn or external sensors, interpret the movement and detect errors. These errors can then be transformed into meaningful instructions to the learner and presented in a multimodal fashion. For example, haptic feedback may indicate an incorrect movement of a limb, while auditory or visual cues could provide additional layers of information. In addition to the multimodal feedback, a computerized system can give consistent, unbiased feedback. This stands in contrast to human trainers which might miss certain aspects of a performance. Interactive systems on the other hand can continuously monitor the movements of the learners to provide uniform feedback. For example, a continuous visual feedback can be placed in the field of view of the participant to which they can glance on demand. An example can be seen in the slackline training system (see Chapter 4) where a visual indicator gives continuous feedback about the participant's posture.

The systems presented in this thesis mostly focus the early stages of learning (see Figure 3.4) and were mostly evaluated over the course of one or two training sessions. As outlined above, feedback is most beneficial within those phases since learners are most reliant on external cues. Evaluating novices also assures a more or less homogenous baseline in terms of the initial knowledge of the participants, making it easier to compare individual trials regardless of the subject being tested. During the early learning phases, the fastest progress in learning can be observed. This also increases the likelihood to observe and measure more significant changes in performance that can be compared between conditions in an experimental study setup. While omitting subsequent retention trials prevents any conclusions about long-term use of the systems, studies during the early stages of learning still give valuable insights into how such systems can be designed and tested. These findings could even inform the design of systems that target the complete learning process, including expert training systems.

Another point of focus was set on giving feedback during the exercise with only little overlap into pre- and post-exercise feedback (see Figure 3.3). When giving feedback in the moment of the movement, the learner has the chance to immediately correct an error. In the case of repetitive movements, this also helps to avoid repeating an error multiple times, reducing the likelihood of learning a wrong movement. Depending on the form of feedback, the system can reduce the amount of information to a minimum to reduce the cognitive load of the learner when decoding the information given during the feedback. Where appropriate, we also integrated pre- and post-exercise feedback, as demonstrated in the slackline training system (see Chapter 4). In this case, participants were given a video instruction of the upcoming exercise and a post-performance analysis, which also doubled as motivational tool.

Using interactive systems that provide in-situ augmented feedback offers significant opportunities to extend the capabilities of traditional human coaches or even serve as a replacement when a coach is not available. The following section gives an overview of such interactive systems designed to aid in the learning process of sports movements, as presented in previous research.

3.2 INTERACTIVE SYSTEMS IN SPORTS AND REHABILITATION

The following section aims to provide a broad overview of application systems that have been developed to assist in learning a movement in the context of sports or rehabilitation.

As mentioned in section 3.1.2 learning a new motor skill or refining an existing one often requires detailed feedback to guide users towards optimal performance. For this, systems have been developed that can support the learning process for movements of varying complexity, ranging from adhering to a gait pattern [127, 204] to performing a 3D motion task like rowing [206, 208]. To communicate feedback or instructions regarding the user's performance, different modalities such as auditory, haptic, and visual, or combinations thereof have been investigated. This section categorizes and discusses these systems. It focuses primarily on those providing feedback during performance but also addresses systems that deliver pre- or post-execution feedback. Works that focus on more fundamental aspects of certain feedback modalities are addressed in the following chapters describing the presented artifacts in this thesis.

This section is organized into subsections based on the primary feedback modalities used of the presented systems and studies. It starts with auditory systems, which utilize sound cues ranging from simple signals to complex sonification for spatial and temporal guidance. The next subsection explores haptic systems, including vibration, electronic muscle stimulation (EMS), and robotics, which provide localized tactile feedback. Visual systems are then presented, covering displays integrated into sports equipment, the environment or on-body wearables. This is followed by a section on virtual, augmented, and mixed reality (VR/AR/MR) systems, covering feedback methods such as mirror metaphors, which augment the user's reflection with additional information or instructions, and ghost metaphors, which overlay a target motion for comparison

3.2.1 *Auditory Systems*

Auditory systems have been used in the past to guide users into the correct movement. To convey the information necessary for this guidance so-called Auditory Displays [100] are deployed. They can transmit content, ranging from very low information density such as a simple, possible very short audio cue to high information content such as verbalized instructions. A simple audio cue like a "bing" sound can primarily convey binary information such as positive ("reached the right posture") or negative ("overstepped a goal") feedback. While this might be sufficient for simple movements or as an additional feedback for already internalized patterns, this simplified information does not serve as directional or temporal guidance in *how* to reach a certain goal such as a posture or movement. To convey this more complex instruction, more information needs to be carried by the sound. This increase of information can be achieved for example by changing the audio signal from a binary cue to a constant signal that is modulated in terms of pitch, timbre or stereo channel. An example for that is provided by Konttinen et al. [125] who presented an interactive system to train precision shooting. Their system utilized concurrent auditory feedback to guide the user during the exercise: When aiming closer to the target, a frequency modulated audio signal would change pitch based on the aiming offset to the target. Additionally, an audible cue would notify the user in case of excessive forward trunk displacement, acting as knowledge of performance during the task. They conducted a study in which they tested their system over a four-week period against a knowledge of results condition in which participants only got information about their precision displayed on a screen after each trial and a baseline condition in which participants were asked not to follow any specific training. The results showed that the group receiving continuous auditory feedback demonstrated more accurate shooting performance than those in the knowledge of results and control group. However, during the trials, there was no difference in performance between auditory feedback and knowledge of results.

In this example, sound in the form of a continuous signal was used to guide the user's arm to aim towards a fixed goal. When performing a more complex movement, such as a rehabilitative arm exercise, the goal - in this case, the position of the joints - moves over a period of time to follow a certain, ideal trajectory. By adding these additional constraints, the requirements for an auditory display increase accordingly. To match these requirements, different approaches have been investigated by applying them to various use case, such as in golfing.

O'Brien et al. [170] used real-time sonification feedback to guide a swinging motion of a golf club. The sonification in the form of a modulated signal was either a replay from an optimal movement or closely linked to the deviations from that ideal swing pattern. The ideal motion was obtained by averaging multiple recordings of successful puts performed by the participants themselves. In a between-subject study, the baseline condition was tested against three conditions: the replay of a sonified version of the own averaged performance, a real-time error sonification rendered through a stereo display (i.e. auditory signal panning to the right when the deviation to the optimal movement is small and vice versa), and a sonification that modulated the audio signal to be "rough" in case of a larger deviation or smooth to evoke wind speeds in the positive case. While all participants improved their putting performance (final distance to the hole), no group differences in performance could be shown. However, the error-based sonification helped participants reduce variability in the execution and timing of their movements. In *AudioMove*, Xia et al. [244] present a spatial audio-based limb exercise guidance system designed for multi-directional movement training without visual feedback. A combination of headphones including an inertia measurement unit and a smartphone was used to render spatial audio in the horizontal plane. The smartphone was attached to the limb to be trained and captured the orientation in the vertical plane relative to the target position. An audio signal indicated if the target position was hit. The authors evaluated the system by testing the inclusion of head orientation versus limb orientation within the spatial audio signal. They concluded that including the head motion data resulted in better accuracy of the motions.

While the above examples require a certain amount of interpretation by the user, another approach is to use (synthesized) verbal instructions that guide the user towards a goal or through a movement. Ramsay and Chang [187] proposed, a system that guides visually impaired climbers during an ascent of an artificial climbing wall by giving verbal instructions regarding the position of the next hand or foothold. These verbal instructions were then complemented with immediate tonal guidance, with pitch and volume adjusting according to the climber's proximity to a hold. A preliminary study, despite not utilizing a real climbing wall, but a Twister playing field mounted on a wall, showed promising results regarding the understandability of the feedback.

In summary, auditory displays offer versatile methods for providing movement guidance. Depending on the sophistication of the displays, they can encode spatial, temporal, and directional information. While basic sounds like cues and tones can efficiently communicate binary feedback, more elaborate auditory displays employing pitch modulation, timbre variation, and stereo effects enable users to interpret detailed positional and movement-related guidance.

3.2.2 *Haptic Systems*

The examples above solely target the auditory system of the user, which has limitations in perception - especially in precise directional and positional information transfer. Haptic systems directly interact with the skin of the user or even actuate the user, allowing for a much more direct and localized guidance or notification. With the skin being the largest sensing organ of the human body, using it as a receiver of information has been leveraged by several interactive systems in the past. Induced sensations can range from changes in temperature [167, 220], the dragging or tapping of actuators on the skin [64, 107], to vibration in different levels of detail [5].

In sports and movement guidance, vibration is a prevalent method to convey localized feedback on the body. Similar to the audio displays described above, the information that tactile actuation can convey depends on the utilization of both the actual signal and the physical layout of the actuators. In the simplest case, discrete, binary signals have been used to indicate a direction for the user to rotate toward or a body part on which to shift the user's weight.

For example, Spelmezan [212] instrumented snowboard riders with vibration motors to guide them through a descent of a ski slope. Vibration motors on both shoulders were used to direct a turning movement, while two vibration motor on the thighs would indicate a weight shift to the rider. A conducted study showed mixed results. The tactile instructions were generally perceived helpful, but less so in the very beginning of learning how to snowboard. As a conclusion, the authors suggest that the system would be most beneficial once basic skills are acquired.

Valsted et al. [229] introduced a breathing assistant for running that used vibration on the wrist as a feedback channel. Based on the cadence of the runner, the vibration indicated the right moment to either start inhaling or exhaling to achieve an optimal breathing pattern. The authors conducted a within-subject study to investigate which vibration pattern was more suitable - a feedback pattern based on exhaling or inhaling. They found that runners preferred the exhale-based feedback over the inhale-based guidance, as it felt more natural.

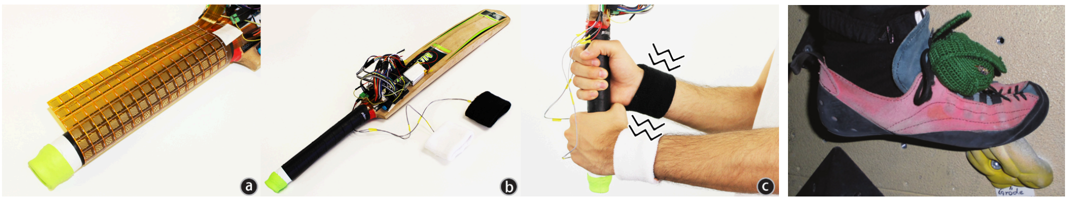


Figure 3.5: Two examples of systems providing body-worn vibrational feedback. Left: Vibration motors on the wrist provide feedback on the grip strength during a cricket pitch [162]. Right: Vibrational feedback on a climbing shoe gives insights in applied foot pressure and hasty movements [65].

By adding different vibration patterns to a single actuator, the amount of information that can be transmitted is increased. Muthukumarana et al. [162] demonstrated a cricket grip strength assistant. Two vibration motors on each wrist indicated the grip strength after batting in cricket, either through singular vibration on one wrist or a pattern on both sides to indicate the relative difference in grip strength (see Figure 3.5, left). A preliminary study showed that participants' perception of gripping strength improved significantly when using the system.

In ClimbingAssist [65], vibration motors were placed on the ankle of a climber to give feedback in cases of insufficient foot pressure applied on a foothold, as well as feedback for hasty movements (see Figure 3.5, right). Here, two different vibration patterns were used to differentiate the feedback. They evaluated their system by collecting qualitative feedback from participants after a short period of climbing. The results indicate that the system's feedback helped participants focus on foot movement.

Instead of using different vibration patterns, employing more tactile actuators across the body increases the spatial guiding capabilities of this modality. This approach was used by Peeters et al. [179] in a study that investigated the placement of tactile actuators on the body, such as the spine or thighs, for the use case of road cycling. The vibration feedback was used to convey information during workload (i.e., exhaustive pedaling) to indicate posture correction. In their study, they compared vibrotactile cues at different positions during varying levels of workload intensity. The recognition rates remained similar across all intensity levels, but response times improved significantly at higher intensities, which the authors attributed to heightened focus and adrenaline effects. Cues on the spine showed better recognition and faster response times than thigh cues, suggesting greater effectiveness for stationary regions in cycling applications.

While the example above employed vibrotactile actuators across the body, the density of actuators was relatively low. Increasing the number of actuators per area offers the possibility to convey continuous directional information, as demonstrated in the next system. In VibroSleeve, an array of vibration motors was arranged on a cylindrical forearm surface to convey arm guidance cues in all cardinal directions [182]. Directional cues were mapped based on forearm sides (e.g., dorsal for "upwards"), while intensity variations were used to convey distance (see Figure 3.6). A preliminary study on stimulus localization

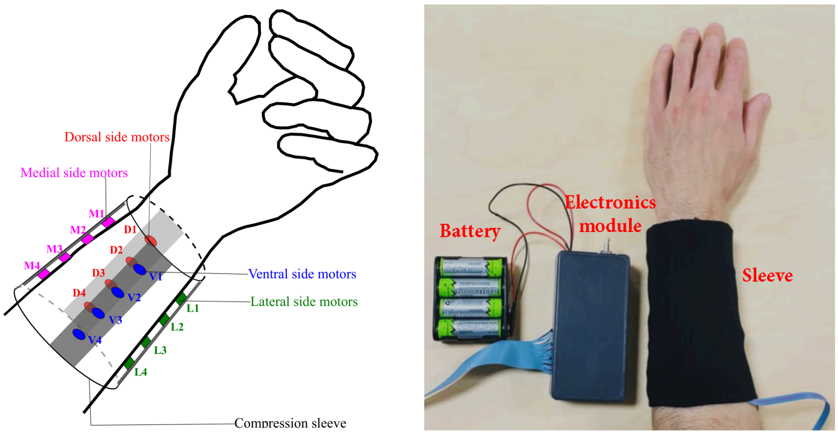


Figure 3.6: An example for a vibrotactile body-worn device capable of giving directional cues via a matrix of vibration motors placed around the underarm of the wearer [182].

investigated intensity discrimination and directional perception when using the actuator matrix. The results indicated that participants could accurately identify vibration location and direction.

The methods described here mostly guide users towards a change in motion or direction, indicated by a vibrotactile stimulus. Other systems directly induce motion of the human body, either passively through robotic devices or actively by means of electronic muscle stimulation (EMS).

EMS is capable of inducing effects ranging from a tingling sensation on the skin to actual muscle contraction and, thus, the movement of a limb [180]. This is achieved by placing two electrodes on a muscle, which then apply a small current that elicits the described tingling sensation or movement. Depending on the current, this EMS signal can be used as a notification channel or to physically guide a user's motion. Tatsuno et al. [219] used EMS to guide the swinging motion in bowling. Electrodes were applied to the forearm of the bowler and were used to induce a twisting motion of the wrist to correct the rotation of the hand. A user study showed that after using the system, a 32% improvement in performance was observed in the participants.

Similar to that, the *GeniePut* system [62] actuates the user's wrist in real time to align a golf club's angle with the target. EMS was applied in two distinct modes: movement augmentation and actuation. In the augmentation mode, the EMS signal was used to gently support the user's natural movement, while in actuation mode, the EMS signal fully controlled the angle of the wrist. This control was ensured by blindfolding the participants in this mode. An evaluation of the two modes against a baseline condition showed that the augmentation mode performed best, closely followed by no augmentation.

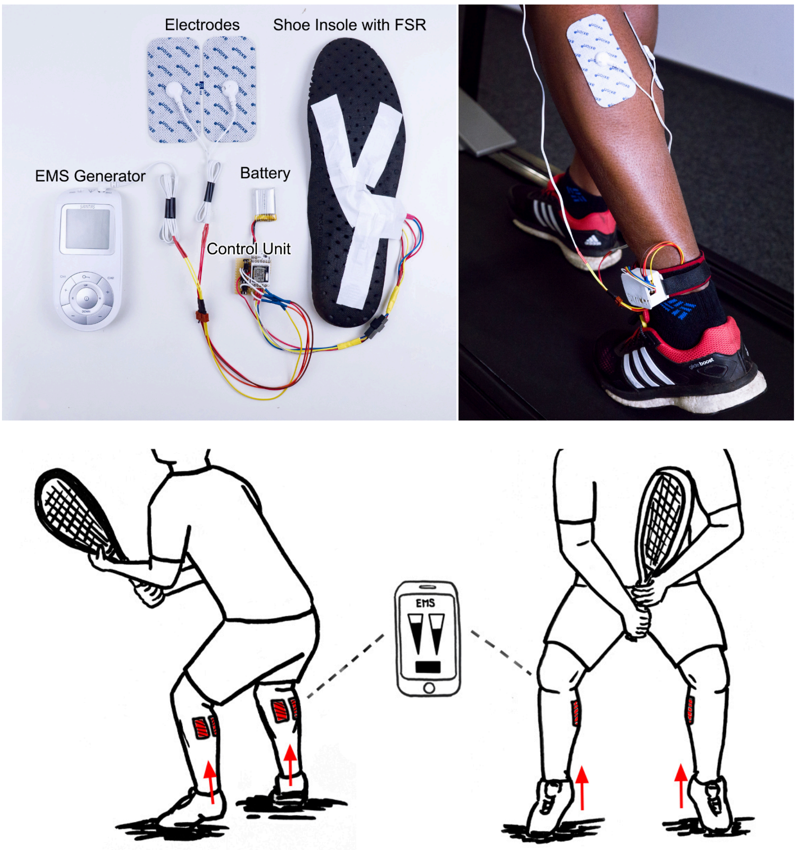


Figure 3.7: Two examples for electronic muscle stimulation of the calf muscles. Top: EMS actuation is used to actively alter the running style [97]. Bottom: Correcting the stance in racket sports [63].

In *FootStriker*, electrodes were applied to the calf muscles of a runner to induce a forefoot running style [97]. A sensor insole detected when the foot made contact with the ground heel-first (see Figure 3.7, top). This triggered an actuation of the calf muscle during the flying phase of this foot, resulting in tipping the foot forward and guiding the runner into the forefoot running style. A study showed that muscle actuation could induce a change in running style, even for a short period of time without further actuation. Also targeting the calf muscle, *EMStriker* addressed the stance in racket sports [63]. In a qualitative study, the authors evaluated EMS actuation in comparison to vibration feedback on the calf (see Figure 3.7, bottom). They concluded that EMS might be better suited than vibrotactile feedback for communicating the correct action to be executed.

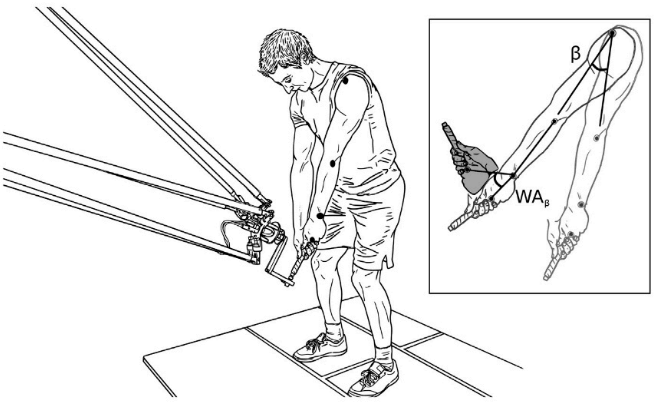


Figure 3.8: Two examples for robot aided motion guidance. Left: An endpoint controlled robot manipulating a handle of a racket [138]. Right: An exoskeleton supporting in gait training [136].

While the systems described above rely on the correct actuation of muscles through EMS, robotic systems have been used to actively move parts of the user's body. This can be achieved by either attaching individual body parts to a mechanism or by actuating a proxy that is held by the user, which then moves the rest of the body in accordance with said proxy. An example of this is given by Kümmel et al. [138], who actuated the handle of a golf club through an endpoint-controlled robot (see Figure 3.8, left). By holding onto the handle, the robotic system guides the user through a swinging motion. They evaluated the system during a two-week training program, including a pre-, post-, and retention test. Two different wrist bending techniques during the backswing were tested against a baseline condition. The results of the study showed that robotic haptic guidance successfully shaped the movement pattern of the complex backswing motion in golfing.

Instead of using a proxy object, exoskeleton-like systems can be used for direct movement of the human body. In such systems, body parts are strapped onto an actuated robotic fixture. The robotic system can then be used to fully actuate a limb, actively support a motion, simulate resistance, or restrict the range of motion in one or more degrees of freedom. These systems were originally designed for paralyzed people to enable them to stand and walk again [231]. Krishnan et al. [136] used *Lokomat*, a commercially available robotic system for gait training that combines a treadmill with a lower limb exoskeleton. The exoskeleton can be individually configured to offer different levels of support or intervention (see Figure 3.8, right). In their application, the exoskeleton pushed participants towards the right gait pattern if deviation from the optimal pattern was too high. An evaluation showed an improvement in performance that persisted during a follow-up evaluation after six weeks.

The examples presented illustrate the versatility of tactile and haptic feedback systems in sports and movement guidance. Since the actuation is applied directly to the user's skin or body, feedback can be given directly at the relevant limb or body part. Depending on the method used, vibrotactile feedback can serve as a notification [65, 162, 179, 212, 229] or provide guidance [182]. Using EMS [62, 63, 97, 219] or robotics [138] allows for the actual movement of different body parts.

3.2.3 *Visual Systems*

As another modality, visual systems have been implemented for movement guidance and learning. This section covers visual systems that are either integrated into the sports equipment, attached to the human, or display information on a screen in front of or around the user. More immersive systems, such as varieties of augmented or virtual reality systems ranging from cave-like environments to applications employing head-mounted displays (HMDs), are covered in section 3.2.4.

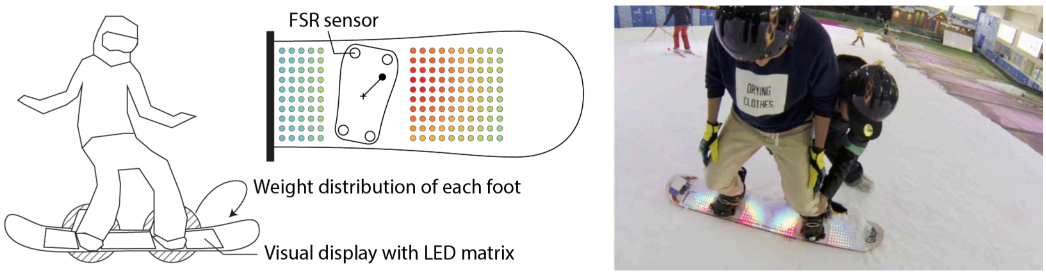


Figure 3.9: An LED matrix applied to the top side of a snowboard shows the weight distribution of the rider in real-time [177]. The visualization can be used by both, the rider and the coach.

Park and Lee [177] studied snowboarding by attaching an LED matrix to the top surface of a snowboard. Pressure sensors were mounted under the bindings to measure the weight distribution of the rider. This setup allowed for the visualization of different characteristics during the descent, such as the distribution of weight, displayed via a colored heatmap (see Figure 3.9). To evaluate the system, two scenarios were tested regarding the impact on movement awareness, user engagement, and instructor feedback. In the first scenario, participants rode individually, while in the second scenario, they were paired with an instructor. The study demonstrated that visual feedback helped riders better understand weight shifts and balance. In lessons, the instructors were able to use the snowboard visualizations to give specific, objective instructions.

Ananthanarayan et al. [6] integrated monochromatic electroluminescent wires into a knee brace (see Figure 3.10, left). In combination with bending sensors, this form of display was used to indicate the knee bending angle during rehabilitation exercises. To convey goal achievement or motivational feedback during running Müller et al. [160] incorporated electrochromic displays onto the outer surface of a running shoe (see Figure 3.10, middle). The toe box segments lit up progressively as goals were approached, while the side displays showed the shoe's wear status (e.g., "okay" or "worn out").

Figure 3.10: Three examples of wearable systems that use visualizations as primary output modality. Left: Electroluminescent wires integrated in a knee brace indicate the knee bending angle [6]. Middle electrochromic displays attached to the outer fabric of a shoe is used to display goals and status of the shoe [160]. Right: Swimming goggles with RGB lights in the peripheral vision of the swimmer are used as navigational aid [121].

Harrison et al. [96] implemented small devices with LEDs that could be attached to the user's clothing at different body locations. The LEDs were used to direct the user's attention to specific body positions. A study was conducted in which participants received randomized notifications throughout a two- to three-hour normal work routine. Whenever the LED on a device lit up, a button on the device had to be pressed to measure the speed of perception. The LED positioned on the wrist was perceived the fastest, while notifications on the shoe resulted in the slowest perception time.

Kiss et al. [121] addressed the navigation of open water swimmers by augmenting swimming goggles with colored LEDs (see Figure 3.10, right). Two different visualization techniques were implemented. The heading was either visualized through a change in the color of the LEDs or by illuminating the left or right LEDs to guide the wearer in the corresponding direction. Two system conditions—continuous feedback through colored light and discrete feedback in case of deviation—were tested against a baseline condition. Kiss et al. concluded that neither method resulted in better navigational precision. However, advanced participants preferred discrete feedback for deviations, while novices favored continuous feedback.

What the systems above share is that their displays conveyed very limited information due to their low resolution in both color and pixel density. Using actual screens enables more explicit information and guidance.

For example, Kooyman et al. [126] proposed a system that offered post-performance feedback in golf putting. Feedback was given in the form of a video recording of the user's putting movement, augmented with visualizations of performance metrics such as putting speed and velocity. A preliminary study showed that after training with the system, the tempo and consistency of the putts improved.

Video recordings of one's own performances have a long tradition in sports training [7]. Using interactive systems, this form of feedback can be automated and augmented. Hämäläinen [93] used a large portrait-oriented display that showed the trainee from the perspective of the camera while displaying a looped, delayed recording of a certain movement. The playback was either triggered automatically or controlled with speech input or gestures. In a follow-up project [94], focusing on martial arts, a system was developed that showed the movements of the user in exaggerated movie- or comic-like interpretations on a large projected screen. While not specific to movement training itself, the authors found that the system could be used to motivate people to train.

Displays as described above require different amounts of the user's attention. While some displays target the peripheral vision of the user [96, 121], other use cases allow the display to be placed directly in the user's focus during the exercise [6]. The usage of actual screens and monitors enables the display of a large amount of information that can be presented concurrently with performing the exercise [93, 126], though at the cost of consuming cognitive capacity that might otherwise support movement performance.

3.2.4 *Virtual, Augmented, Mixed Reality*

Besides displays that are integrated into sports equipment or attached to the user, immersive technologies like Augmented Reality (AR), Virtual Reality (VR), or Mixed Reality (MR) — which blends elements of both - offer the potential to provide very specialized and targeted guidance during movement learning.

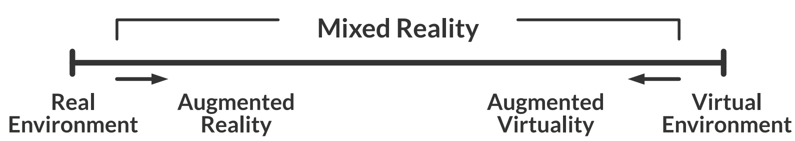


Figure 3.11: Milgrams Reality Virtuality Continuum [156].

Immersive systems that guide the user may not always be bound to one of these technologies. Rather, they can be positioned on a continuum such as the Reality-Virtuality (RV) Continuum by Milgram [156], meaning that there is gradual transition between e.g. augmented and mixed reality instead of a discrete distinction. In simplified terms, AR systems enhance the real world with overlaid text or images while maintaining a strong connection to reality. MR systems on the other hand blend real and virtual worlds, allowing real and virtual objects to interact with each other seamlessly. Finally, VR systems replace the real world entirely with a fully virtual environment, ideally immersing the user in an environment that is disconnected from the real world. The examples introduced in the following sections gradually follow the RV Continuum, progressing from AR through MR to VR systems.

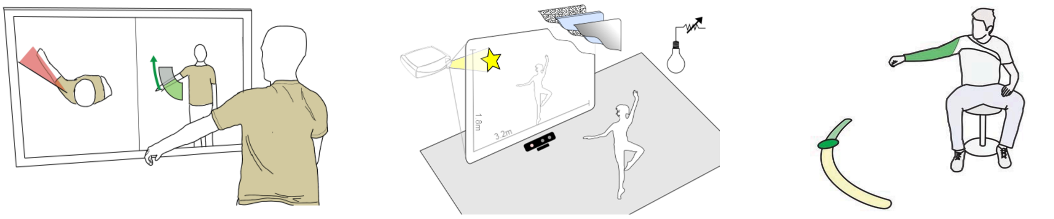


Figure 3.12: Three examples for movement guidance using Augmented Reality. Left: On-screen AR superimposes instructions onto a live recording of the user [218]. Middle: The reflection of the user in a semi-transparent mirror is superimposed with target positions [10]. Right: Instructions are directly projected onto the user and the floor [211].

In *Physio@Home* Tang et al. [218] augmented a live video recording of a user in front of them on a screen. Their application guided users through upper body rehabilitation movements. To guide the movements, different visualizations which were overlaid over the live video feed indicated in which plane, direction, and to what extent an arm needs to move (see Figure 3.12, left). In addition to a frontal view of the user, a second mode introduced a side view of the user. A user study revealed that this second mode led to the least deviation in movements.

Using projections instead of screens allows adding information to the surrounding of the user without occluding too much of the physical world. Projected visualizations can be displayed on the floor, walls or even sports equipment. This approach is demonstrated in [204] by augmenting a treadmill with projections on the walking surface. Projected footsteps and barricades indicate where users should step on and nudge them to adjusting their stride length. In a study, the projected guidance was tested against a visualization displayed on a screen in front of the participants, which showed a real time representation of the participants feet in addition to the target footsteps and barricades. Results showed that the projected guidance condition led to greater accuracy and reduced the time participants could adapt to gait changes. Projected guidance also received higher ratings in terms of user experience and intuitiveness.

In *SleeveAR* an interactive assistant was introduced that guides upper body exercises through projections on both the floor and the arm by Sousa et al. [211]. The arm was augmented by colored projections to indicate whether it was in the right position while projections on the floor showed the movement direction (see Figure 3.12, right). To evaluate the system, the augmented projection was compared against video instructions without real-time feedback. Participants reported that detecting misalignment was easier when using the augmented projection. This finding was supported by significantly better scores in replicating the demonstrated exercises.

Moving closer to MR, Anderson et al. [10] introduced *YouMove*, a setup for dance movement training consisting of a semi-transparent mirror with a projectable layer as output (see Figure 3.12, middle). During training, the user could see themselves in the reflection of the mirror, which was augmented with visualizations to indicate correct or incorrect posture. When comparing the system with traditional video demonstrations, the authors found that participants performed significantly better using their system. The same concept was expanded upon by Zhou et al. [249] for general movement learning. Instead of a simplified skeleton visualization of the trainer, as used by Anderson et al., this system displayed the trainer as a 3D avatar. Additionally, the head position of the user was taken into account to better match the physical reflection to the virtual avatar projected on the screen behind the semi-transparent mirror. In a study, the authors tested two modes of their system: physical reflection augmented with a display, and a display with a rendered reflection—against a baseline condition using video instruction. They found that the physical reflection mode provided better depth information and a better sense of agency, with some limitations for movements involving large head movements. Both systems share the benefit of allowing users to simultaneously see themselves in a natural and accustomed setting while receiving corrective feedback from a virtual trainer.

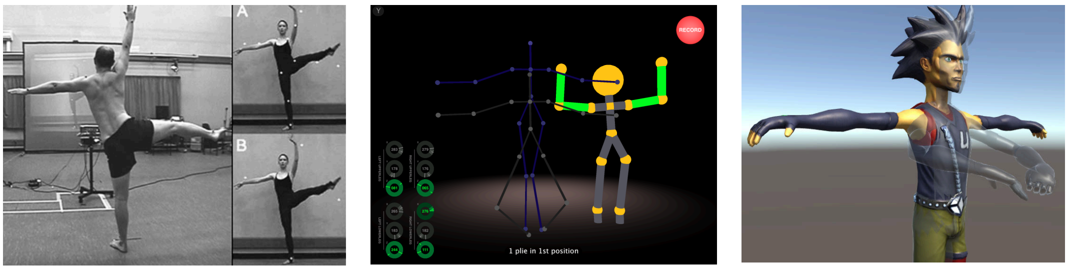


Figure 3.13: AR and VR examples for guidance systems in dancing. Left: Superimposed target joint positions are rendered on a live video feed [55]. Middle: On-screen AR superimposes instructions onto a live recording of the user [218]. Middle: Skeletons of trainer and trainee on a screen [149]. Right: Usage of the Ghost metaphor to aid the alignment of trainee avatar to trainers target pose [18].

Other approaches omitted the physical reflection and used a purely virtual representation of trainee and trainer, sometimes augmented with additional information in form of overlays. One application for this method is (ballet) dancing [18, 55, 149]. Eaves et al. [55] superimposed a real-time video recording of the trainee with visual markers that represented the joint positions of a trainer performing the motion in an optimal fashion (see Figure 3.13, left). When comparing different feedback amounts in the form of visual markers for six or four joint positions, the authors found that the full six markers resulted in better performance during trials while feedback given with only four markers would result in better performance in retention test. In *Super Mirror* [149] trainer and trainee are visualized as skeletons on a screen (see Figure 3.13, middle). Both skeletons are displayed side-by-side, allowing the trainee to compare their own pose to the optimal one demonstrated by the recording of a trainer 8s. The results of a technical evaluation suggested that the proposed method is suitable for simple poses. Similar to that Barioni et al. [18] used 3D avatars instead of skeletons. Instead of showing both avatars side-by-side, a ghost metaphor was chosen which superimposed the trainees' avatar with a translucent version of the trainers' avatar (see Figure 3.13, right), allowing for an in-situ comparison of both. The system's usability was tested with 22 participants, half with and half without ballet experience. During the study, five arm positions were practiced by the participants while receiving real-time feedback. A questionnaire assessed usability. Ballet-experienced participants rated the system highly for clarity and assistance in maintaining the correct form while novices expressed the need for additional guidance.

Naour et al. [163] presented a system to give post performance feedback to a roundoff exercises by means of motion capture and 3D visualization of trainer and trainee on a large screen. Here, different visualizations were proposed, showing, similar to the example before, trainee and trainer side by side, but also with the option to move the camera freely instead of sticking to the mirror metaphor. Feedback was presented after each performance. In a study, four different feedback methods were compared: video recordings from two perspectives as a baseline, 3D animations from two perspectives, the same 3D animations overlaid with the participants' performance from two perspective, and the same visualization again but with participants having the ability to freely move a virtual camera to observe the movement from different angles. The performance of the trials was manually assessed by judges as well as analyzed using time series data from the motion capture system. While the assessment of the judges favored the 3D animations with an overlay of the participants performance no evidence of this could be shown in the quantitative data analysis. In a similar system Oshita et al. [173] expanded on this idea by enhancing the augmented 3D animation with overlaid user performance. To facilitate the interpretation of the deviations, the authors proposed to add arrows that indicated the direction in which to move or rotate a body part to.

The examples presented above share the common output medium of either a screen or a large projection limited to a single dimension. In contrast to that, *CAVE*-like systems [40] use large scale projections surrounding the user to induce a sense of immersion in a virtual environment. When adding physical props to this visualization, such as handles of rackets or rowing oars, various training scenarios can be implemented.

Waltemate et al. [233] developed a technical system implementing a low-latency virtual training environment (see Figure 3.14, right). To render three-dimensional content, specialized projectors and polarized glasses were employed. The motions of the user were captured using an optical tracking system. This implementation resulted in a setup that allowed for a mirror metaphor as already seen in the previous examples.

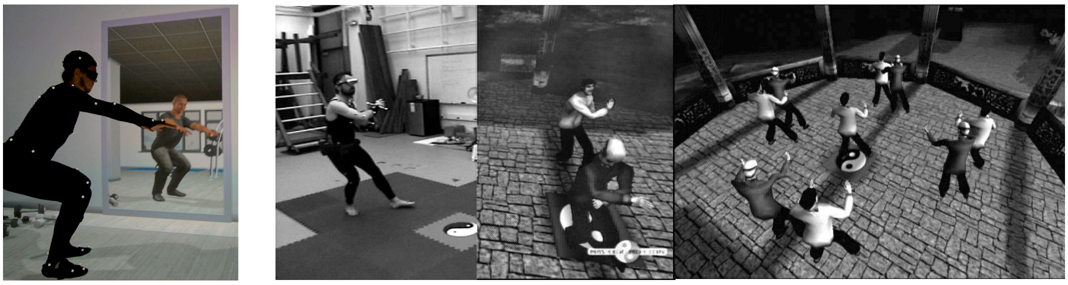


Figure 3.14: Two examples for VR rendered via a CAVE or HMD. Left: A virtual mirror shows the trainees reflection superimposed with the trainers avatar [233]. Right: Different visualizations of Tai Chi trainee and trainer displayed in an HMD [34].

Using HMDs (Head-Mounted Displays) allows for even more immersive training environments. Chua et al. [34] proposed a system for Tai Chi movement training. An optical marker tracking system capturing the trainee's skeleton was combined with an HMD to explore different visualization methods for trainee and trainer (see Figure 3.14, right), using avatars. This included visualizations in which trainees could see themselves from different viewing angles, in combination with a superimposed avatar of the trainer. A user study showed that none of the more sophisticated visualizations resulted in better performance than the classical instruction method, where the trainer stands directly in front of the trainee. With what are considered simplistic graphics by today's standards, a martial arts training system was proposed in [124], confronting the trainee with a virtual opponent to provide feedback on attack and defense movements. Subramanian et al. [214] proposed a rehabilitation system that placed the user in a virtual elevator, where the task was to press several buttons. Reaching for and pressing the buttons resembled upper body rehabilitation movements. They evaluated the effect of performing the exercises in immersive VR by comparing it to executing the same exercises in a physical environment. To replicate the virtual environment, they suspended physical buttons in the air. In a between-subject study, the authors found that both groups benefited from the training, regardless of the presentation. However, participants training in the virtual environment (VE) showed an increased joint range of motion and decreased compensatory trunk movement. Furthermore, those who exercised in the VE reported higher enjoyment compared to the other group.

Kojima et al. [123] employed the ghost metaphor, as seen in [18], in the context of baseball pitching. In their implementation, the user viewed a first-person perspective through an HMD. A skeleton of a trainer was superimposed over the representation of the user's body. Instead of following the pitching movement in real-time, the movement was split into 17 poses, which the users were instructed to assume one after the other. In *Onebody*, a remote posture guidance system was presented [101]. 3D cameras were used to record the skeletons of both the trainee and the trainer. The trainee was presented with a simplified representation of both skeletons from a first-person view, allowing for real-time matching of the trainer's movements and posture. A within-subject study compared Onebody's performance against three alternatives: a pre-recorded video, Skype, and third-person VR, where participants saw a visualization of themselves superimposed with the trainer's visualization. Performance was assessed in terms of posture accuracy, completion time, and subjective user ratings. The Onebody system demonstrated significant improvement in upper body posture compared to the other methods. However, completion time was longer.

In conclusion, immersive technologies such as augmented reality, mixed reality, and virtual reality demonstrate great versatility in providing guidance during movement learning. Projections on both the environment and the user's body have been used to assist users in following a movement [204, 211]. Different approaches to augmenting a representation of the user allow for extensive expert modeling. Common techniques aimed at aiding users in copying the movements of an expert are the mirror and ghost metaphors. The mirror metaphor allows users to see a representation of themselves in a physical or digital mirror, often augmented with additional information such as directional guidance [55, 218] or avatars whose movements can be copied in real-time [10, 18, 149, 233]. Using an HMD enables users to step into the "ghost" of a trainer, often visualized as a translucent representation of the trainer's body in the form of an avatar or stick figure [101, 123].

3.2.5 *Mixed Systems*

The following section summarizes systems and studies that either combine or compare multiple output modalities in their ability to give feedback during movement learning.

An example of a multimodal system is provided by Paay et al. [176]. During an iterative design process, they developed an assistive system for weightlifting training. The system combined automatic verbal instructions during the exercise with a screen in front of the users, displaying a post-exercise analysis of their performance. The verbal instructions guided the user in real-time during the exercise (e.g., *"Keep your shoulders over the barbell"*) when deviations were detected. A qualitative study of the final design iteration revealed that a combination of different output modalities was considered useful by all participants. However, some participants stopped mid-lift to listen to the verbal instructions, suggesting that verbal instructions might require too much attention during strenuous activities. The post-performance analysis was perceived as particularly helpful by all participants.

Broadening the scope of application, *GymSole* was developed by Elvitigala et al. [56] to provide corrective feedback during the execution of various gym exercises. A pressure-sensitive insole was combined with eight vibration motors arranged around a sports shoe (see Figure 3.15, left). The insole measured the center of pressure (CoP), which should remain on the heel of the athlete during squats and deadlifts. During the performance, the tactile display formed by the vibration motors indicated the current position of the CoP. To evaluate the system, a within-subject study was conducted, comparing the vibrotactile feedback to a baseline condition with no feedback and a visualization of the CoP displayed on a screen in front of the participants. In addition to the CoP, posture was evaluated using optical tracking data. The authors found that both tactile and visual feedback resulted in a significant improvement in body posture; however, no difference was found between the two feedback modalities. While some participants favored the vibrotactile feedback since it did not require maintaining focus on the screen, the graphical visualization offered greater precision.

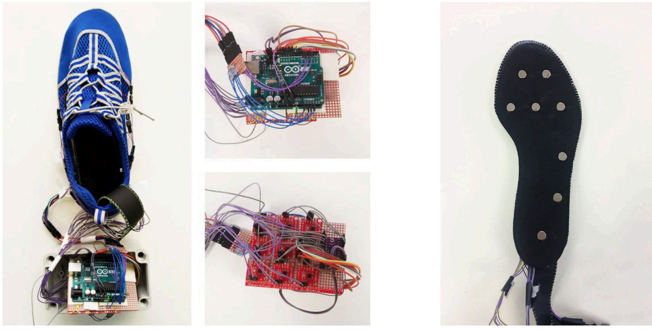


Figure 3.15: Iterative design process of a tactile, foot-worn feedback system to support weight lifting by indicating the center of pressure by means of a pressure sensitive insole. Left: Vibration motors added to the outer shell of a shoe [56]. Right: Integration of vibration motors directly in the insole [57]

In a second iteration [57], the vibration motors were directly integrated into the insole (see Figure 3.15, right), and a Google Glass device was used to visualize the current CoP. The two new methods were compared to the previous shoe setup with external vibration motors and the screen-based display in front of the participants. Both new feedback methods were compared to the previous shoe and display method in a qualitative user study that assessed usability and user preference. While no significant differences were found in either category, the vibrotactile insole scored slightly higher than any other condition in terms of usability. The authors concluded that vibrotactile insoles appear to be a good choice for CoP feedback.

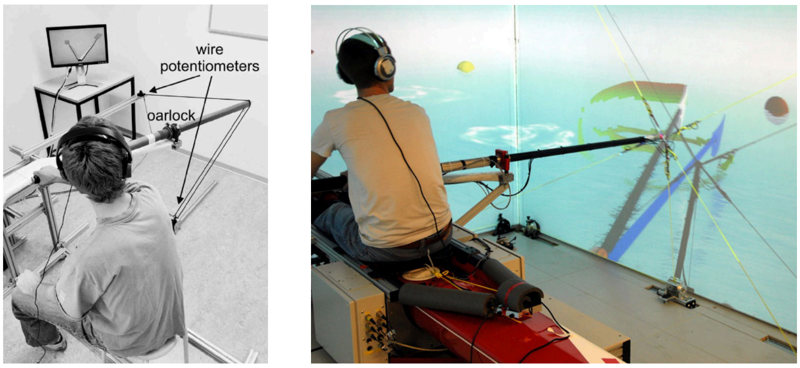


Figure 3.16: Two study setups investigating different output modalities in a rowing task. Left: Comparing audio to visual feedback on a screen [206]. Right: In addition to audio, tactile feedback as well as an immersive CAVE like visualization was added [208].

In a series of works [206, 208], Sigrist et al. developed a rowing trainer to investigate how feedback should be designed to assist the learning of a complex motor task. The task in all experiments was to execute a rowing movement with an oar, following and adhering to an optimal trajectory and blade angle. In [206], two consecutive experiments were conducted in which the authors compared audio guidance to visual feedback (see Figure 3.16, left). The audio feedback consisted of differently modulated continuous signals that indicated deviations from the optimal movement. For example, the stereo channels indicated deviations on the horizontal axis, while pitch modulation (and later additional features, such as a chord becoming increasingly out of tune) provided feedback for deviations on the vertical axis. Whenever the blade orientation exceeded a threshold around either 0° or 90°, the audio signal changed from a sine wave to a raspy sawtooth wave, accompanied by a change in timbre. For visual feedback, the authors implemented several visualizations, ranging from a simple 2D cross-section of a blade to 3D ghost metaphors of the oar, similar to the VR examples above, later augmented with a trajectory to follow. In general, the authors found that visual feedback was more effective than auditory feedback. They attributed this to the auditory feedback being less intuitive than the visual feedback. However, they suggested that a longer familiarization phase with the auditory channel might improve performance. In a subsequent experiment [208], the authors added tactile feedback and replaced the screen with an immersive projection to the user's right, showing a virtual representation of the oar (see Figure 3.16, right). Furthermore, a visual terminal feedback condition was introduced, displaying an overlay of the participant's trajectory over the optimal path. The results of the study showed that terminal feedback outperformed concurrent feedback. However, the authors argued that concurrent visual feedback demonstrated potential to instruct complex movements, while haptic feedback supported temporal aspects of a movement. They concluded that combining multiple modalities is a promising approach to aid in complex motor learning.

Bieńkiewicz et al. [21] compared visual and auditory cues in golf putting. Specifically, their system was designed to assist in retaining the correct speed and velocity during swinging motions. In contrast to most systems described above, this system focused on replaying a recording of an expert without indicating any possible deviations in the user's swing. An LED bar along the swing's movement area was used to indicate the position of the golf head in the recording via a moving light. For the audio condition, the expert's recording was sonified using a modulated audio signal (white noise) and stereo channels, producing a "woosh" sound resembling a golf club moving through the air. Both conditions resulted in improved performance, but no significant differences were observed between the auditory and visual feedback methods.

Marchal-Crespo et al. [148] introduced an assistive system for tennis forehand stroke training. A stick mimicking a tennis racket was held by the user, while a roped robot manipulated the end of the stick, effectively controlling its pointing direction. In a study, the authors compared different forms of haptic guidance, varying the degree of autonomy provided, along with an additional condition that supplemented visual feedback to the haptic guidance. They concluded that haptic feedback is particularly beneficial for novices, while visual feedback is better suited for more advanced users.

Instead of actuating the sports equipment, as in the tennis racket example above, Koritnik et al. [127] used a lower limb exoskeleton in combination with visual and audio feedback for a stepping-in-place task. The task consisted of varying cadences and hip angles that needed to be tracked by the participants. In a within-subject study, different combinations of haptic and visual feedback were examined. The visual modalities varied by showing either two 3D avatars (trainer and trainee) superimposed over each other or just a 3D avatar of the trainer performing the gait pattern. Haptic feedback was provided by the exoskeleton using an impedance-based control strategy, meaning there was perceivable resistance when the legs moved in the wrong direction or a slight push when a leg remained stationary but needed to move. The results of the study showed that adherence to the gait pattern was superior in the haptic condition compared to the visual feedback modalities. Combining both haptic and visual feedback resulted in even better performance.

This section summarized systems and studies that either combined different modalities or compared them against each other. Paay et al. [176] as well as Elvitigala et al. [56, 57] investigated different output modalities in weightlifting. While Paay et al. found that with real-time verbal instructions, participants stopped mid-lift to listen to the instruction, Elvitigala et al. reported that either real-time condition - visual and tactile feedback - resulted in a performance improvement. Although no significant difference in performance could be shown, participants favored the tactile feedback. In complex tasks such as rowing, Sigrist et al. [206, 208] compared visual, tactile and auditory cues. They noted that a combination of modalities is a promising approach. While Bieńkiewicz et al. [21] could not show a difference in performance when comparing visual and audio guidance in a golf swing, Marchal-Crespo et al. [148] focused on tennis stroke training and found that haptic feedback is especially beneficial for novices, while visual feedback might be better suited for more experienced individuals. In gait training, Koritnik et al. showed that combining haptic feedback through an exoskeleton with visual feedback improved adherence to movement patterns.

These findings suggest that the choice of feedback modality should be task-specific and considering the user's skill level. Mixed systems might offer significant potential for movement learning by using the complementary strengths of various modalities.

3.2.6 *Challenges in Generalizing Feedback Modalities Across Sports*

Classification of Feedback

The systems discussed in this section demonstrate how interactive systems have been utilized as feedback methods for movement guidance in the past. In addition to a categorization of the systems based on their primary output modality, they can also be aligned on a dimension describing the *information bandwidth*, meaning the quantity and complexity of information a modality can effectively convey to the user. This dimension spans systems delivering feedback with *minimal information* or *high information*. This poses challenges to the design of feedback systems, since receiving, understanding, and acting on the feedback given by a system adds cognitive and physical demands, which compete with the user's primary task of performing a movement. Thus, it seems reasonable to balance the simplicity of the output modality with the richness of information that needs to be conveyed to provide actionable feedback. For example, the system presented by Konttinen et al. [125] could be placed closer to the *minimal information* end of the dimension. They used a frequency modulated audio signal that changes pitch based on the aiming offset to a shooting target. By utilizing auditory feedback instead of visual cues, the system minimizes additional demand on the user's vision channel while still providing effective feedback. Increasing the informational bandwidth is necessary, for example, when the guidance of the movement involves managing multiple degrees of freedom. The snowboard assistive system of Spelmezan [212] illustrates this and could be placed more towards the *high information* direction of the dimension. Here, the system utilized tactile feedback applied to the rider's shoulders and thighs to offer guidance during turning movements while also aiding in shifting the weight during the descent. This highlights how the choice and design of feedback modalities depend on the complexity and demands of the sport targeted.

Feedback Effectiveness Across Contexts

Generally, the review of the research as outlined above demonstrates that assistive systems for sports show promise in improving movement learning through various feedback modalities. However, the findings of the studies were highly context-dependent and may not be applicable to other sports that vary in complexity or movements involved. In golfing [170], auditory real-time error-based feedback did not lead to better performance compared to auditory guidance delivered as a static replay of the optimal motion. Similarly, when comparing visual to audible feedback in golfing [21], both modalities resulted in performance gains, but no significant difference in improvement was observed. However, when comparing visual to auditory feedback in rowing [206], participants performed better in the visual condition. While terminal visual feedback in precision shooting [125] produced smaller performance improvements compared to continuous auditory feedback, terminal feedback outperformed continuous feedback in rowing [208]. When using EMS, notification or augmentation methods outperformed actual muscle actuation in running [97]. Conversely, the same comparison resulted in better performance for EMS augmentation in golf putting [62]. While these are only a few examples, the heterogeneous findings indicate that results from studies investigating different or multimodal feedback methods in complex sports cannot be easily generalized or transferred between sports and feedback methods.

The same appears to apply when trying to transfer insights gained from studies investigating simple motor tasks to more complex movements (see [150, 239, 243], as cited by [207]). In the context of rehabilitation, Winstein suggests in a literature review that learnings from laboratory experiments should be seen as guidelines rather than exact recommendations when applied to real-world applications [239]. In her review, she emphasizes that this is especially true when trying to transfer insights from one-dimensional to multidimensional movements.

Similarly, based on another literature review, Wulf and Shea argue that motor learning principles derived from simple tasks may fail to address the multidimensional challenges of complex skills [243]. They conclude that more research is needed to include more complex motor tasks, enabling the development of practical recommendations for real-world applications. A concrete example of the difference in the effectiveness of feedback frequency is provided by Marshall et al. [150]. They argue that frequent augmented feedback is detrimental in a laboratory setting but does not have the same effect in the context of sports-related tasks.

These examples collectively underscore the variability in feedback effectiveness across contexts. This highlights the need for a detailed investigation of novel feedback methods in underexplored complex and dynamic sports. Two such sports are rock climbing and slacklining, which both have unique demands regarding balance, coordination, and control.

3.3 ROCK CLIMBING AND SLACKLINING AS CASE STUDIES

To approach the research questions stated in the previous chapter, we implemented a set of artifacts in the form of interactive systems for sports. We chose two different sports to study these artifacts in a realistic setting: rock climbing and slacklining. While in rock climbing the goal is usually to ascend a natural or artificial wall, in slacklining the aim is to balance or walk on a flexible line suspended between two anchor points. Having both, an interactive system and a real-life use case allowed us to conduct research by employing several different methods. Through online questionnaires and interviews with rock climbers, we could gather data that helped us throughout the development cycle of an artifact. Initial insights gathered through online questionnaires were used to inform the conceptualization phases of the artifacts. During user studies, of which some were also conducted out-of-lab in a climbing gym, we could investigate our artifacts with the intended population in a realistic setting, which gave us a more realistic representation of user engagement compared to fully controlled experiments. While this resulted in a more complex study setup compared to a lab study, it allowed for unique opportunities to conduct experiments.

With the choice of rock climbing and slacklining, we picked two sports that gained increased popularity in the early 2000s. For example in the United States, a steady growth of climbing gyms can be observed with a net gain peak of 45 gyms in 2021 and now a total of 622 climbing or bouldering gyms in 2023 [111, 112]. While slacklining is a sport by itself, it is often also used as a meantime activity between ascents during a rock climbing session. Depending on how these sports are performed, they can be done with relatively little gear, preparation, and time commitment. In rock climbing, many climbers dream of a big-wall experience in the Yosemite National Park or an alpine climb in the classic Eiger-Nordwand in the Swiss alps. For most of them, this stays an ambitious goal for the future that is contemplated while packing some rock climbing shoes and strolling around the bouldering block in a local climbing gym. Conversely, it is much less hassle to tie a slackline between two trees in a park instead of scaling two adjacent mountain tops to set up a highline between two peaks in the Swiss Alps.

Having both toned-down versions of the sports makes them very accessible to a broad population thus, making them an interesting object to study.

3.3.1 *Rock Climbing*

Figure 3.17: Two forms of rock climbing. Left: Rock climbing in the outdoors using a top-rope. Right: Bouldering in a climbing gym with only a mat as protection.

Rock climbing as it is known today and displayed during the Olympic Games has a long history and underwent several developments, including gear, variations of the sport and ethics. While the exact roots of rock climbing as a sport are not manifested, Fontainebleau with its upbringing of Bouldering has been named as one of the birthplaces of this sport [250]. The large boulders in various shapes and forms have been used by mountaineers since 1897 to train for actual ascends of mountains. Different "parcours" were imagined that lead the mountaineers from boulder to boulder through the forest, allowing for both, technical and physical training in the form of climbing up and down those rocks [196]. The focus of these early ascents was set on the preparation for mountaineering adventures or scientific expeditions. Here, hemp ropes, ladders, and steel bolts that were driven into the rock with hammers were used for both protection and the actual ascent of a mountain.

Later, in the early 1900s, free climbing was advocated by, amongst others, Paul Preuß [183]. He manifested that aids such as bolts hammered into the rock should only be used for protection, and not for the ascent itself. Following this philosophy, new mobile protection tools were invented such as so-called cams (spring-loaded camming device), that can be placed into cracks to then attach a rope to them. Today, this form of rock climbing is called *traditional climbing* in which not only came are used to protect from a sudden falls but also so-called nuts, which are a small pieces of metal that are stuck into cracks, sometimes as narrow as a few millimeters.

In the last several years, a new style of climbing emerged that generally focuses on the athletic aspect and the physical exercise of the climbing activity. The latter is today known as *sport climbing*, differentiating itself from *traditional climbing*. While the beginnings of rock climbing, as the name suggests, started out in the outdoors, indoor rock climbing or bouldering gyms began to appear in larger cities, with the first one opening in Seattle, Washington, USA in 1987 [174]. In these gyms, both hobbyists and professionals can indulge the sport in different ways. Bouldering gyms offer a variety of artificial boulders and walls that are surrounded by thick mats to cushion a sudden fall (see Figure 3.17, right) and only require a pair of climbing shoes that can often be rented in the gyms. In dedicated climbing gyms, the walls are much taller and require a rope to safely ascent and repel from the wall. Here, climbers have the option to use so called *top-rope* routes where the rope is already attached at the top of the wall and can be used by a pair of climber and belayer. Alternatively, in so-called *lead climbing* the climbers start with the rope tied into their harnesses at the bottom. As they ascent, they clip the rope into carabiners that are most of the time already attached to the walls. Usually, these artificial walls present a grid of threads that are used to mount artificial holds of various shapes and colors. These holds can be very large, very small or something in between. Very large holds can be grabbed with both hands or even "mantled" on, meaning to press down on the hold with both hands until one can eventually stand on the hold itself. Other very small holds might only support one or two fingertips (see Figure 3.18).

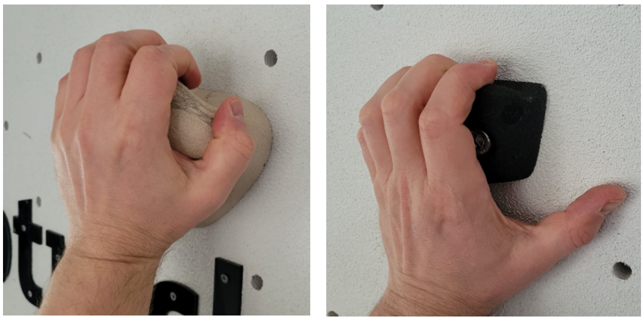


Figure 3.18: Different types of rock climbing holds. Left: Large climbing hold that can be grabbed with the whole hand. Right: Small climbing hold that only supports the fingertips.

Artificial climbing walls (see Figure 3.19) are equipped with colored holds for hands and feet. Although the amount of holds mounted to the wall is large, only a few are part of a specific route and are allowed to be used. Often this subset of holds that form a route, is

Figure 3.19: A climbing route is composed of a number of different holds (often of the same color, or marked with colored tape). Only these holds are allowed to be used.

indicated by holds of the same color. Other times, colored tape stuck next to holds is used instead. When ascending a route, only the holds that belong to a route are allowed to be grabbed or stepped on.

This simple rule allows for ample opportunity to make up for a very easy or almost impossible ascent. Route setters, the individuals who design the routes, strategically place different holds onto the walls, taking into account existing features such as overhangs, slants and corners. How easy or hard a route is perceived by the climber depends on different factors. This begins with the slant of the wall. An overhang is usually more strenuous to climb than a slant, a part of the wall leaning away from the climber. Second, the shape of the holds plays an important role (see Figure 3.18). If the route consists of a lot of "jugs", holds that can be held like a handle of a mug of beer, it is usually one of the easier ascents. Smaller holds on the contrary are usually harder to grab and more difficult to place a foot on. Finally, the build of the climber is another factor. If the holds are placed very far apart, a taller climber with a wide arm span will have an easier time climbing that route compared to a smaller person. On the other hand, a route that requires some crouching to reach a hold might be easier to climb for this smaller person. To quantify how hard a route is, different difficulty scales were introduced. However, as outlined above, the perceived difficulty highly depends on the climber, which makes it hard to give an objective difficulty measure for a route [47].

When setting a route, the route setter can influence the difficulty of the ascent in different ways as outlined above. Depending on how such a route is set, an ascent can be mastered by brute force or carefully administered technique. While the former is sometimes necessary, especially for routes where a dynamic move such as a leap to the side or up high is required, ascending the route with visible ease and grace is considered more elegant and desirable, also from a physiological standpoint [197]. To master this, one has to acquire a set of skills, techniques, and endurance.

Ascending a route requires the climber to plan movements either when still on the ground or during the ascent itself. Depending on the complexity of the route, high cognitive and physical demand is imposed on the athletes [81]: This includes but is not limited to, being able to precisely step on foot holds, being in control of one's center of mass and moving it so that gravitational forces do not pull the climber off the wall. Finally, physiological parameters such as endurance are important to conserve enough energy to reach the last hold of an ascent before the forearm flexors cannot contract anymore due to exhaustion.

All these challenges present ample opportunities to design assistive systems for rock climbing. These systems could target very localized problems such as being in control of the contraction of the forearm flexors to more generic applications such as communication tools that are adapted to the high cognitive load of the climber during an ascent.

3.3.1.1 *Rock Climbing and Human Computer Interaction*

Climbing is a complex activity that is determined by a variety of physiological and anthropometric factors. Mermier et al. [154] found that the variance in climbing performance can be mainly explained by a set of trainable variables and less by specific anthropometric characteristics. While the physiological factors of climbing have gained some research attention, there has also been research on the cognitive factors of climbing [166]. In wearable computing and HCI, climbing received more and more attention in the last years. Some related work exists regarding instrumented climbing walls, automated skill assessment, route recognition using a wearable device, and augmented reality [4, 43, 73, 114, 128, 140, 143, 175].

Various approaches have been proposed to track a climber using body-worn sensors, image processing, or instrumented climbing walls. Liljedahl et al. [143] proposed Digiwall, which consists of holds that can sense the climber's position with built-in capacitive sensors and provide subtle feedback with LEDs. The focus of their work was gaming, competitions, and challenges that can be rather used for playful activities than rigorous training. A very similar instrumentation was done by Ouchi et al. [175] whereas the goal of their work was to model play behavior of children. They used climbing holds that incorporated a LED and a strain gauge to detect utilization of the hold. Their work aimed at improving the design of age-appropriate and safer playground equipment. Aladdin and Kry [4] proposed an instrumented climbing wall for static pose reconstruction. They used holds equipped with 6-axis force torque sensors that were used to reconstruct the climber's pose during an ascent. An evaluation showed that dynamic motions and higher errors coincided. Fuss and Niegl [73] also used torque sensors in instrumented climbing holds to measure the performance of a climber. Data collected on three climbing events has been segmented into three phases of contact: set-up phase, crank phase, and lock off.

While the previous methods required an instrumented climbing wall, Ladha et al. [140] used wrist worn accelerometer sensors to assess climbing performance. An evaluation of the system during a climbing competition resulted in a positive correlation between the predicted and the actual score of the participants. In previous work we introduced ClimbSense [128], a system to record and automatically recognize successfully climbed routes. In this approach, the climber was equipped with wrist-worn Inertial Measurement Units (IMUs). The IMUs were used to collect a set of climbing data and train a classifier that is able to recognize different routes, ultimately allowing for a qualitative tracking approach in regard to route characteristics that has not been possible before.

Daiber et al. [43] investigated handheld augmented reality for collaborative boulder training. They presented a mobile augmented reality application to define, document, and share boulder problems. Kajastila and Hämäläinen [114] also explored augmented reality for climbing walls by directly augmenting the wall with a projector. A preliminary Wizard-of-Oz study with six interaction prototypes and structured interviews showed that users liked the system. In a later iteration of the system, a fully fledged augmented reality rock climbing system has been proposed which was eventually commercialized [116].

Mencarini et al. [153] explored emotions in novice climbers. From interviews with beginner climbers, they conclude that haptic feedback can improve communication between climbing partners to manage negative emotions.

A first approach to VR climbing experiences is presented in Chapter 8. The "Venga!" system by Tiator et al. [225] is a follow-up project that implemented both, hand and foot tracking and proposed a simple approach for hand and feet calibration. Their calibration approach requires the user's extremities to remain at a certain location during the calibration phase. Recently, Schulz et al. [202] investigated the role of physical props on presence, stress, and anxiety in VR climbing. They compared actual, unaugmented climbing in 10m height, fully immersive virtual rock climbing as described above, and virtual climbing using controllers, similar to the VR game "The Climb"[2]. Using the VR setup including physical climbing increased the anxiety and sense of realism perceived by the study participants. Gao et al. [76] investigated the sensory and perceptual factors in simulated climbing environments.

2 http://www.theclimbgame.com/

While climbing has received increasing attention in the broader context of HCI as outlined above, the specific aspect of movement guidance during climbing remains underexplored, presenting an opportunity for further investigation and development.

3.3.2 *Slacklining*

Figure 3.20: Two forms of slacklining[3]. Left: Someone slacklining in a park. Right: A long slackline set up in the mountains.

Slacklining is a form of tightrope walking. In contrast to the steel tightrope one might know from a circus, a slackline is a wide nylon webbing. This allows the material to stretch and bounce, which in turn resembles it as a very narrow trampoline. An experienced athlete can use these properties to not only walk back and forth on a slackline but also to perform jumps and flips.

3.3.2.1 *Slackline Origins*

Modern slacklining, as it is lived today, has its roots in the 1960s and 1970s as spare time activity of rock climbers [74]. Between ascents, the climbers experimented with rigging nylon webbing, which was part of their climbing gear, between trees and rock formations to eventually build up enough balance to walk on the early version of a slackline. In 2007 the first slacklining company - Gibbon Slacklines - was started in Germany which then sold slackline kits with ratchets and other gear to tension the slackline between two fixed points [12]. Today, slacklining has grown in popularity with a dedicated community and events such as competitions and outings.

With the diversity of people practicing that sport, different forms of slacklining have evolved as well. The most approachable form is probably casual slacklining in a park. Similar to bouldering, this is a very social sport that lives from interaction between participants to share tips and experiences. To start, webbing is tensioned with a ratchet between two trees.

3 Left: Picture by Michelle Raponi taken from https://tinyurl.com/mrxzhfuw, Right: Picture by Constantin Goldann taken from https://tinyurl.com/yymjbxyn

As large forces are applied on the fixed points when walking on the slackline, padding is used to protect the bark from damage.

Building on that, tricklining includes various acrobatic maneuvers while walking on the slackline. This includes jumps, saltos and bouncing on the slackline with different body parts. For this, athletes use the dynamic nature of the webbing which acts like a small trampoline. Out of this form of slacklining competitions arose in which athletes are scored based on difficulty, style, and execution.

Two other forms that focus more on the properties of the setup of the slackline are Longlining and Highlining. As the names suggest, in Longlining, the aim is to walk on a slackline that spans a large distance. The current record is held by three Germans after they walked 2130m on a longline setup over the Lapporten valley in the Abisko National Park, Sweden[4]. Unlike shorter setups, longlines require greater focus and precision to maintain stability over extended distances. Respectively in Highlining, the goal is to walk over a slackline that is set up at significant heights above the ground. For this, the slackline is anchored between mountain tops or buildings. Athletes are usually protected by a harness that is linked to the slackline via a rope. While not performed between actual fixed points, as of 2021, the current height record was set by Rafael Zugno Bridi from Brazil who walked on a slackline that was suspended between two hot air balloons in a height of 1901 meters[5].

3.3.2.2 *Slacklining from a Research Perspective*

Except those extremes, slacklining is an accessible sport for a diverse range of individuals. In addition to its recreational benefits, slacklining has gained recognition for its therapeutic applications in all age groups [74, 75, 80, 82, 108, 195]. Foundational research has been conducting, investigating the effect of slackline training to balance, in both, children and seniors [49, 50, 53, 223]. The benefits of slackline training as supplement to the training of other sports could be shown in youth soccer [67, 226], soccer warm up [108], and judo [194].

From a Human Computer Interaction perspective, various works have been presented focussing on balance. A substantial body of works addresses balance training for different age groups using different techniques such as augmented reality [159], virtual reality [203], or tangibles [215]. These training often entail the use of gamified elements [22, 113, 141]. Vertigo, a sensation of spinning that often disrupts balance, has been explored in games before, especially using vestibular stimulation [28–31].

While the examples above illustrate the focus on balance within interactive systems, there is little work addressing the unique challenges of slacklining. Specifically, the factor of vertical swaying movements of the nylon webbing has not been fully addressed in HCI systems. There is a very limited body of works addressing slacklining specifically. Forystek [70] instrumented a slackline with LED strips and a motion sensor. The motion

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4 https://tinyurl.com/yv4st6n3
5 https://tinyurl.com/yc654yxm

sensor measured the acceleration of the slackline in the horizontal and vertical direction. This acceleration was then color coded and displayed on the LED strip mounted below the slackline to give feedback to the athletes on their performance. Anlauff et al. [11] proposed an interactive system that would give augmented feedback while training a single leg stance on a slackline. Here, leg bending and upper body posture where used as parameters to provide knowledge of performance to the users using a sonification approach.

3.3.2.3 *Opportunities for Interactive Systems*

Especially for beginners, it is difficult to walk or even stand on a slackline. What seems to be an uncontrollable swaying and moving of the webbing may be very frustrating at first. Mastering these movements requires a substantial amount of balance, core body strength, and focus [51]. For this reason beginners often start with basic balance exercises and drills, gradually building confidence and coordination on the line. For this, several exercises were designed with a focus on the individual aspects of successful slacklining [137, 181, 222]. While these exercises and techniques are explained in books and videos, individual instruction that adapts to the current needs of the beginner may lead to a faster learning experience.

This challenge could be met by assistive systems that can capture the athlete's posture and give real-time instructions as seen in the sonification system above [11]. A different approach that goes beyond supporting the single leg stance, but rather guiding through a training schedule how to walk one a slackline is demonstrated in the following chapter.

Part II

IN-SITU FEEDBACK SYSTEMS

The second part of the thesis explores the development, implementation, and evaluation of interactive systems that provide in-situ feedback to support learning in sports. Chapter 4 presents a slackline training system that offers real-time guidance and post-exercise analysis for slacklining. In Chapter 5 we investigated wearable feedback for rock climbing, focusing on cognitive demands and notification channels. Finally, Chapter 6 investigates real-time visualizations of climbing movements to improve technique. Together, these systems span the dimensions of feedback from low to high information content (see Section 3.2.6), with a primary focus on real-time feedback while incorporating elements of pre-movement instructions and post-exercise analysis.

4 REAL-TIME INSTRUCTIONAL FEEDBACK IN SLACKLINING

As described in the previous chapter, slacklining with its high demand for balance and focus serves as interesting object of investigation for real-time feedback system. In this chapter, we present the implementation and evaluation of an interactive slackline training assistant. This chapter addresses **RQ 1**, **RQ 2** and **RQ 3** by focussing on real-time feedback with a high information content. The contents of this chapter were previously published under the following publication.

Felix Kosmalla, Christian Murlowski, Florian Daiber and Antonio Krüger. "Slackliner - An Interactive Slackline Training Assistant". *In: Proceedings of the 26th ACM international conference on Multimedia.* MULTIMEDIA'18, Republic of Korea. [131]

4.1 INTRODUCTION

In this chapter, we address the opportunities for interactive training systems for slacklining addressed in Section 3.3.2. Slacklining, with its high demand for balance and coordination, poses a significant challenge to master, especially in the early beginning when learning this sport. This challenge is mostly addressed by utilizing detailed instructions, either through books, videos, or in the best case through personal trainers in the form of friends or acquaintances. However, as outlined before, this personal, detailed form of feedback is not always available out of different reasons (see Section 2.1).

To overcome this issue, we present an interactive slackline training assistant. It guides trainees through various exercises, monitors their performance in real-time, and gives instant feedback on how to improve their movements. Additionally, a post-analysis provides the trainees with more detailed feedback about their performance. With this, we address the stage of early learning and utilize feedback pre, post, and during the exercise.

We evaluated the system in a between subject study in terms of usability and performance increase by asking 12 slackline novices to either train with an expert or the proposed interactive slackline training assistant. The results of the study showed that both groups improved their slackline capabilities significantly. We could, however, not show a significant difference in post study performance when comparing the results of the participants using the system versus those who have been instructed by a human trainer. User feedback collected after using the system indicated that the interactive slackline training assistant can be used as an enjoyable and effective alternative to classic training methods.

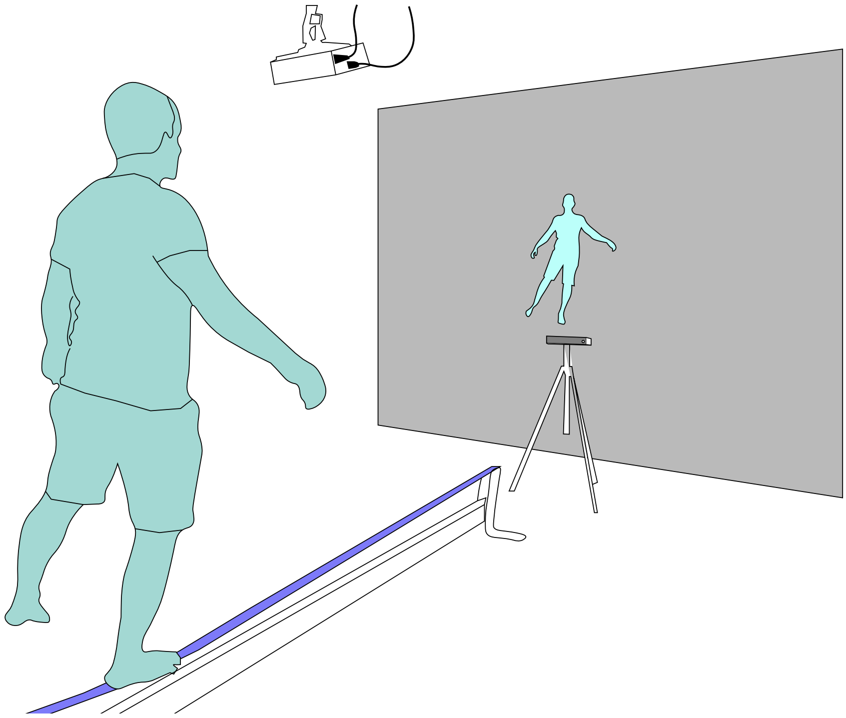

Figure 4.1: Setup of the slackline training system. The slackline is placed in front of a projected display. A Kinect facing the users tracks their movements. Real-time feedback instructs the trainee during the exercises.

The primary contribution of this chapter is a user study comparing the training effects between our interactive slackline training system and the classic approach with a human trainer. Furthermore, the design and implementation of the system represents a contribution in itself, since it could be deployed in a variety of ways ranging from rehabilitation to fitness gyms as well as home use. In addition to that, we provide lessons learned, as interactive slackline training systems had not been studied to this extent in the past.

In the following we describe the conceptualization, implementation, and evaluation of a slackline training system. Since the system is supposed to give real-time feedback on user performance, we review different tracking methods that have been used in similar applications in past research. This is followed by the conceptualization by the system, describing the identified requirements such as user interaction and training regimen. Next, based on the concept, the implementation is detailed, including how tracking and how the different aspects of real-time feedback were implemented. The study setup and result analysis is concluded with a summary of the findings. Finally, we present the contributions of this chapters to the research questions in this thesis.

4.2 BACKGROUND AND CONTEXT

The use of technology in sports has given athletes and trainers new possibilities in training and analysis. Video recordings are still a widely used tool to analyze performance and give insights to both trainers and trainees. However, in those scenarios, the interpretation of movements is left to the users.

More sophisticated approaches use varied sensors such as (depth) cameras, motion-, pressure- or bending-sensors, delivering digital data that can be analyzed programmatically to give objective measures on performance. Depending on the features to measure, design decision have to be made which sensors could be deployed and where to place them. For the latter, different approaches have been presented in the past. If applicable, sensors can be placed on the sporting device itself. For example, Kooyman et al. [126] used a gyroscope on a golf club to assess putt tempo. A snowboard was fitted with pressure sensors under the binding to measure the center of gravity of riders by Park and Lee [177], while a pressure sensor matrix wrapped around the handle of a cricket bat to assess the grip strength of the batter [162].

To directly measure aspects of the movement of the athletes themselves, sensors can either be placed on the user or in the environment. Examples for sensors employed on the user's body are pressure sensitive insoles [56, 104, 212, 247] or bending sensors in knee braces [6]. For a more complete picture of whole body movements, complete sensors suits using inertia measurement units (IMU) that combine accelerometers, gyroscopes, and magnetometers can be employed [176]. Here, different commercially available solutions have been brought to market in recent years (see e.g. Xsens[1]) that usually entail a set of IMU sensors placed on every limb segment. After a calibration, biomechanical models can then estimate the bodies configuration and location with a high precision. However, these models are usually fine-tuned to common human movements such as walking, running, jumping, etc., and may lead to incorrect representation when e.g. rock climbing or slacklining.

As an alternative, optical tracking systems use cameras deployed in the environment and capture the athlete from different viewing angles (e.g. OptiTrack[2] or Vicon[3]). These motion capture systems have been used in the past to analyze motions in tennis [3, 173], dancing [55], mini-golfing [62] and rehabilitation [211, 218]. What combines these systems is a high precision that comes at the cost of expensive hardware and calibration overhead, limiting their use to professional lab setups and training facilities. However, consumer 3D cameras such as the Microsoft Kinect[4], its successors[5], or competitors[6] allow for skeleton tracking applications that is easy to set up and deploy.

1 https://www.movella.com/products/motion-capture
2 https://www.optitrack.com/
3 https://www.vicon.com/
4 https://tinyurl.com/yc6h3fuh
5 https://tinyurl.com/3m925hta
6 https://tinyurl.com/25sy25r7

While tracking with only one camera comes with drawbacks such as a higher chance of wrongly estimated motions due to occlusions, such systems have been successfully used in past research for rehabilitation [33, 61, 164] and balance training purposes [35]. Furthermore, Estepa et al. [61] and Freitas et al. [71] used the Kinect to implement motor rehabilitation games. Motion data collected while playing served as basis for (automated) analysis to be reviewed by physiotherapists. This approach was also integrated by Navarro et al. [164], who proposed a system for that allows balance disorder patients to perform a specific rehabilitation exercise in the comfort of their own home. Additionally, collected data served as basis to assess the rehabilitation process from a distance.

In the system proposed in this chapter, we used the Kinect v2 to track the motions of the users. We opted for this, since the Kinect allows for an easy integration with game engines such as Unity 3D[7], does not require calibration, does not rely on instrumenting the user, and has been used in training and rehabilitation approaches before. Finally, as in the balance system of Navarro et al. [164], we wanted the system to be usable in a home or gym setting.

4.3 CONCEPT

When designing the slackline training system, we aimed to replicate the benefits of a human trainer in an interactive system. The system should, like a human trainer, react to the movements of a trainee and should guide the user through a structured set of exercises, while still allowing to be operated by the users themselves like a computer program.

Training Methodology

Thomann [222] described two teaching approaches for slackline skill acquisition. Both break down slacklining into chunks of skills such as sitting, standing, keeling, walking, or tricks in the form of jumping and turning around, all of which represent a challenge of varying difficulties. These chunks are then prepared as individual training exercise practiced during a training session. Thomann describes the *differential method* as a series of exercises that vary in difficulty. Easy exercises might be followed by harder exercises to be succeeded by exercises that pose a smaller challenge. In the *methodical routine* however, the order of exercises is chosen so that exercises with a slightly higher challenge follow another. We decided to implement the *methodical routine*, since it allows designing a training regimen that incrementally prepares the trainee to eventually walk on a slackline. Furthermore, following a linear progression of exercises facilitates the comparison between the implemented system and a human trainer.

The goal of the slackline training system proposed in this chapter is to teach beginners how to balance on the slackline in a controlled manner, stand on it for a few seconds,

7 https://unity.com/

and be able to walk a couple of steps. Kroiß [137] defined a set of exercises for slackline skill acquisition that were evaluated with school students of different age groups. Similar exercises were proposed by several other works [12, 17, 49, 51, 85, 118, 122, 181, 222] to be included in a training regimen. Out of those exercises, we chose a subset to be included in the proposed system. To structure those exercises, we categorized them into four levels, representing the fundamental basis of the individual exercise routines:

1. Preliminary exercises on the ground
2. Stepping onto the slackline
3. Standing on the slackline
4. Walking on the slackline

Real-Time Feedback & User Interaction

Since the proposed system should replicate the benefits of a human trainer, it should instruct the trainees before each exercise, give real-time feedback during the exercise, and should give a post-performance evaluation. Similar approaches have been presented by Velloso et al. [232] and Anderson et al. [10] who demonstrated real-time feedback systems that supported trainees in weight lifting and general, full-body movement training. In both systems, the user was presented with a mirrored view of themselves, augmented with additional information on form and performance. We chose to provide similar feedback to the users of this system. Before each exercise, the user should be presented with a textual and visual instruction of the movement to be performed. During the movement, the system should continuously monitor the execution while providing real-time feedback and actionable hints on how to improve. To allow unrestricted movements of the user and to avoid unnecessary shifts in position to operate a mouse and keyboard or touchscreen, we opted to implemented midair gestures, similar to what has been presented by Hämäläinen [93] in his martial arts training system.

4.4 IMPLEMENTATION

To implement the system, we chose a mobile slackline (*alpidex POWER-WAVE 2.0*[8]) which stands in front of a projected screen and a Kinect v2 facing the trainee (see Figure 4.5). We used Unity 3D to handle program logic and to visualize a graphical user interface on the projected screen.

8 https://tinyurl.com/34ed4hsz

User Tracking

As outlines above, we decided to use a Kinect v2 to track the trainee since our goal was to develop a system that could be used in a variety of non-professional settings like home use, setup in a fitness gym, or at a physical therapy studio. When positioning the Kinect, we explored multiple viewing angles, ranging from pointing towards the slackline from the side to different angled orientations. Placing the camera on a tripod at waist height in front of the user resulted in the best tracking, although the legs of the trainee might occlude each other during the exercises since during walking, users need to place one step in front of another. The actual recognition of the movements during the training employs a *rule-based* and a *gesture-based* approach. An example for a simple gesture would be standing on one leg while raising the trainees' arms above their head. More complex gestures involved movement sequences like stepping onto the slackline and then stretching one leg to the side. For these gestures, we used the Visual Gesture Builder from Microsoft[9]. The tool uses machine learning techniques that are trained with recordings of movements and produces databases which can then be used within Unity 3D to detect the gestures. However, the gesture recognition system only returns a confidence value for each recognized gesture. This would leave the interpretation in how to improve to the user. To overcome this issue, we also implemented simple rule-based checks that observed relative positions of the individual limbs of the user. This allowed to integrate checks such as *left arm above head* by comparing the vertical position of the hand with the position of the head. Additional rules like *user on slackline*, *leg pointing outwards* could then be added to each exercise. Each exercise consisted of an instructional text, a demo video, the gesture and the rules. These rules are displayed as a checklist during the exercise execution (see Figure 4.3).

User Interface

The user interface comprises different screens that guide the user through the application.

WELCOME SCREEN The welcome screen gives the trainee an opportunity to get accustomed to the projected interface and the gestures to control the system (see Figure 4.2, top row). A small silhouette of the trainee is always shown in the center of the screen to give them feedback on the status of the tracking system. Following the Microsoft Human Interface Guidelines for the Kinect[10], we implemented a gesture based navigation system which allowed users to interact with the system. The position of user's hand controls a virtual cursor on the projected screen. By "pushing" the open palm towards the screen, buttons could be activated.

9 https://tinyurl.com/ycx3ehn8
10 https://tinyurl.com/2c679627

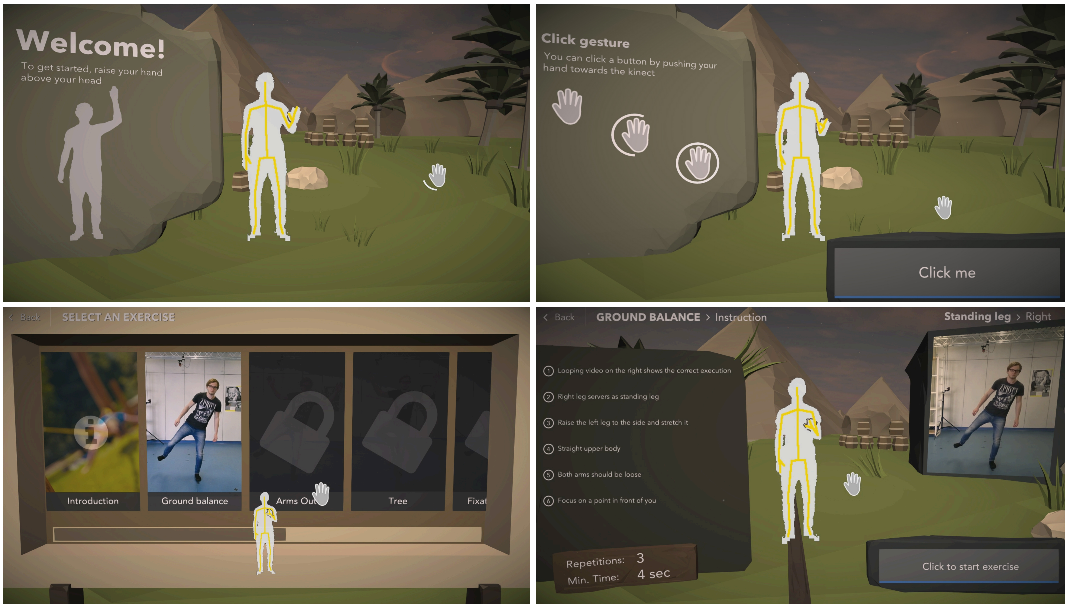

Figure 4.2: A selection of user interfaces of the slackline application. First, the users are introduced to the system and its controls by giving instructions how to navigate via gestures (top row). After selecting an exercise (bottom left), the user gets presented with

EXERCISES The exercises are grouped in levels, as described above. After choosing a level, the trainee can pick an exercise from a list and is presented with instructions and a demonstration video specific to the selected exercise (see Figure 4.2, bottom row).

EXERCISE EXECUTION The exercise execution screen (see Figure 4.3) represents the core functionality of the system. To increase user engagement, we created a playful virtual environment in which we placed several user interface elements. Feedback indicators provide the user with information about their performance in real-time. For this, we chose a set of different visual and auditive elements:

- Checklist about key elements of an exercise (center left)
- Number of repetitions (bottom left)
- Correctness of the performance of an exercise (blue bar on the right labeled "confidence")
- Elapsed time during which the user had been performing the exercise (right to the trainees silhouette)
- Successful completion of a repetition (audio signal, timer color, success text, and incrementing repetition counter)
- Unsuccessful repetition attempt (audio signal and timer reset)

Figure 4.3: During the exercise, the user is supported by real-time feedback giving insights into the current movement quality and how to improve it.

EXERCISE SUMMARY After each successful exercise execution, the trainees are forwarded to a summary screen (see Figure 4.4). There they receive an overview on performance parameters like the execution time, attempts, and the confidence for each repetition. Averaged values summarize these three factors.

4.5 USER STUDY

The system was evaluated in a real-life scenario, teaching novices to walk on a slackline. We compared the Slackline Training System (SLA) to a classic approach with a human trainer Human Trainer (HUM).

4.5.1 *Apparatus*

The apparatus was set up as shown in Figure 4.5. Crashpads surrounding the slackline protected participants from injuries. The slackline was placed directly in front of the Kinect, which was attached on a tripod with a height of 90 cm. Both were placed in front of a wall that was used as a projector screen. A projector mounted on the ceiling of the room projected the system's interface onto the wall. The setup for the human trainer group was the same but without utilizing the projector and the Kinect. To record the execution, a video camera was placed behind the participants to record their actions as well as the interface interaction.

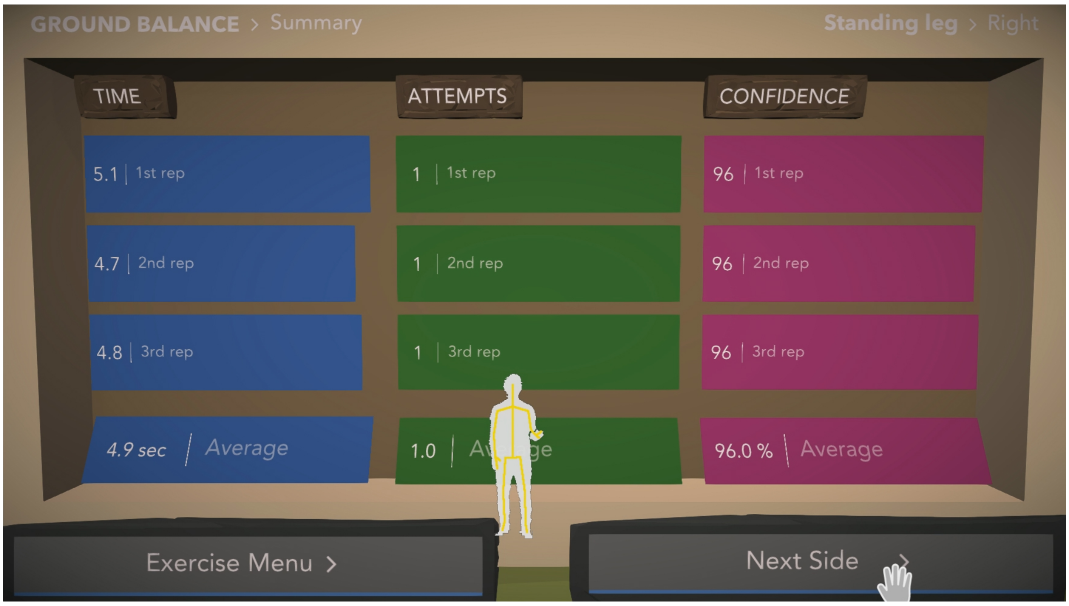

Figure 4.4: After each exercise, the user is presented a summary of her exercise performance considering time needed, number of attempts, and quality of execution.

4.5.2 *Participants*

A total number of 12 participants were recruited (four female). The ages ranged from 21 years to 42 years ($M = 28$, $SD = 6$), the body heights from $154cm$ to $197cm$ ($M = 177cm$, $SD = 12cm$), and the weights from $45kg$ to $112.5kg$ ($M = 75kg$, $SD = 19.5kg$).

More details on demographics are summarized in Table 4.1. The participants' dominant leg was determined with a Lateral Preference Inventory Questionnaire by Coren [38]. All participants had a moderate to strong preference for the right leg. The physical activity level was determined with the Physical Activity, Exercise and Sport Questionnaire (Bewegungs- und Sportaktivität Fragebogen - BSA-F) by Fuchs et al. [72]. It is divided into physical activities including their job, free time, and sport activities.

The participants did not participate in slacklining or other balance training prior to the participation of the study. They showed no history of musculoskeletal disorders that may have affected training or testing. All participants were briefed and gave their informed consent to take part on the study, and agreed to audiovisual data recording. The present study was approved by the local ethics commission.

4.5.3 *Conditions*

We randomly assigned participants to either the Slackline System Group *(SLA)* or the Human Trainer Group *(HUM)*. Both groups were presented with the same levels, exercises, detailed description about the execution, and repetition count. For the Human Trainer

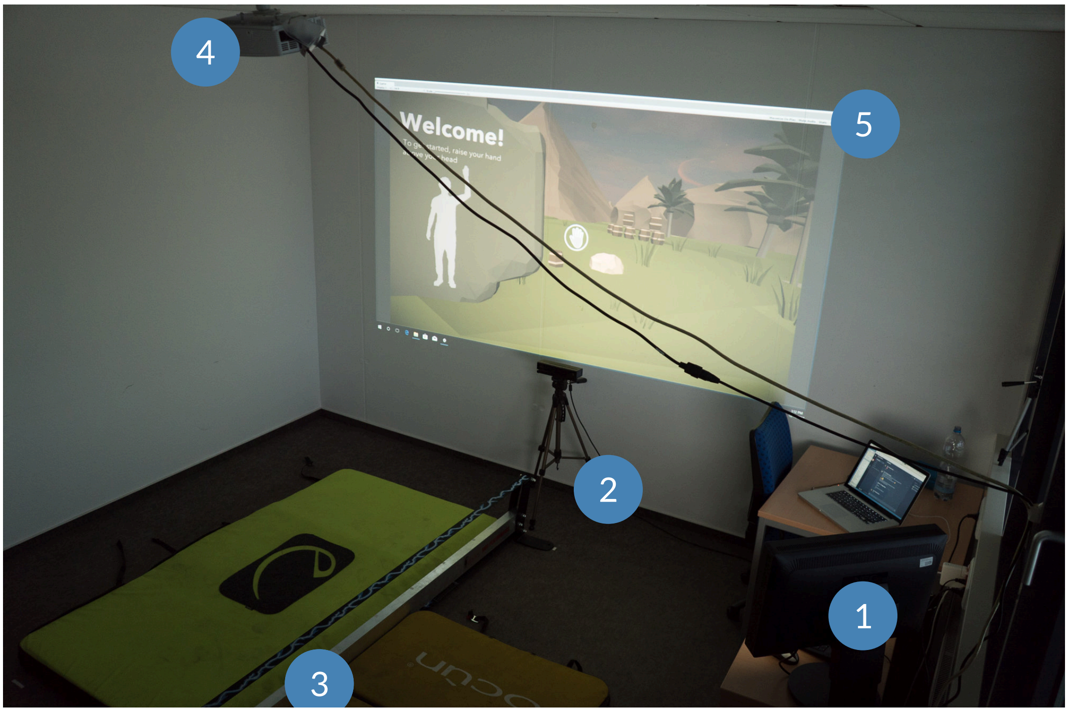

Figure 4.5: Apparatus of the user study. Slackline (3) and Kinect (2) were placed in front of a wall which served as projection screen (5). Crashpads around the slackline prevented injuries when slipping or falling. A computer (1) running the application was connected to the Kinect and a projector (4).

Group, instructions were given by the experimenter, demonstrating the exercise and giving feedback during the execution. Participants in the Slackline System Group autonomously used the system which guided them through the exercises, giving feedback as described above. All participants were using socks but no shoes during the training.

4.5.3.1 *Slackline System Group (SLA)*

The participants interacted by themselves with the system, which instructed them how to interact with the system and guided them through predefined exercises as described above. Step-by-step textual descriptions and a looping video of the correct execution as well as how often and how long a certain pose has to be held were presented before each exercise. During the exercise, the system provided real-time feedback about the current execution performance with several indicators. The participants were encouraged to think aloud while interacting with the system. However, the experimenter did not provide any hints or answer questions, ensuring that participants interacted with the system independently.

4.5.3.2 *Human Trainer Group (HUM)*

In this condition, the participants were instructed by a human trainer. To begin, the trainer provided instructions on the current level, categorizing the exercises. Next, the specific

	SLA (n=6)	HUM (n=6)	Total (n=12)
Gender [f/m]	2/4	2/4	4/8
Age [years]	26 (3)	29 (7)	28 (6)
Weight [kg]	74.2 (18.9)	75.8 (21.8)	75 (19.5)
Lateral FootPreference [index]	3 (1.1)	2.3 (1.4)	2.7 (1.2)
BSA Job [index]	0.78 (0.34)	0.61 (0.74)	0.69 (0.56)
BSA Spare time [min/week]	223.3 (231.6)	181.7 (149.3)	202.5 (187.1)
BSA Sport [min/week]	148.1 (153)	141.1 (101.7)	144.6 (123.9)

Table 4.1: Demographic data of the participants. *SLA*: Slackline System Group; *HUM*: Human Trainer Group. Data is reported as mean with standard deviations (SD). Lateral foot preference index ranges from strong left (-4) to strong right (+4). *BSA*: Physical activity index ranges from low active (0) to highly active (+3)

exercise was explained, focusing on the movement's execution, the number of repetitions to perform, and the minimum duration the trainee needed to hold the pose. Following this, the experimenter demonstrated the exercise for the trainee. An exercise script was used to ensure the trainee received the same consistent information as provided by the Slackline Training System.

4.5.4 *Design & Measures*

We used a 2×2 mixed factorial design with two group levels (SLA, HUM) and two measurement times (PRE, POST). Within subject, a PRE-measurement (before the training) and POST-measurement (after the training) was performed. To evaluate the participants' performance, the following measures were recorded for each foot. Each measurement was taken three times, and the results were averaged for subsequent analysis.

SINGLE LEG STANCE DURATION We measured the time of a single leg stance with the left as well as the right foot on the slackline using a stopwatch.

DISTANCE WALKED We measured the distance walked on the slackline by applying tape to the slackline in $50cm$ intervals.

STEPS WALKED To account for different stride lengths, we also counted the number of steps a participant was able to walk on the slackline.

All PRE- and POST-measurements were video recorded for later transcription.

4.5.5 *Procedure*

At first, the participants were briefed about the study procedure according to the assigned condition and informed consent was obtained. This was followed by a questionnaire collecting demographics and prior experience with slacklining. Participants of the Slackline System Group were asked to answer one more question about their prior experience with motion-based, interactive devices (e.g. Kinect, Wii, PlayStation Move, etc.). Lateral preference and physical activity level were assessed as described above.

To screen for balance disorders, participants with a balance disorder, they were asked to perform a single leg stance on the right, and then the left foot. This was repeated on both the ground and then on a rolled towel. Participants underwent three trials of ten seconds each. When all trials could be completed successfully we deemed those participants to having no issues maintaining balance on a stable and uneven surface.

Following this, participants underwent the PRE-measurements. First, a single leg stance for the left and right foot on the slackline with a maximum of 10 seconds was performed. Then, participants were asked to walk from one end of the slackline to the other. The measurement was done for a run starting with the left leg as well with the right left. For each measurement and leg, the participant had to perform three trials, resulting in a total of 12 trials.

After the participants completed the PRE-measurement test, a short introduction about the following procedure was given: When starting an exercise, participants had to start by standing on a marked position on the floor. Then before each performance, the exercise was described, including an introduction of the movement, how many repetitions had to be performed and depending on the exercise, how long to hold the pose (e.g. standing on the slackline with the right leg extended). This description was provided by either the Slackline System or the human trainer. During the performance, feedback was also delivered by the respective system or trainer. An exercise had to be repeated until all repetitions were completed successfully. If an exercise was perceived as too hard, participants could skip it and continue with the next one, or take breaks at their discretion. After each exercise, we assessed the perceived difficulty on a scale from 1 (very easy) to 5 (very hard).

A POST measurement was performed after all exercises were completed by the participant, following the same procedure and measures as the PRE measurement.

Finally, a semi-structured interview was conducted to obtain user feedback. Questions covered their experiences with the training method according to the participants assigned condition. Additionally, participants training with the Slackline System were asked about the user interface and their experience with the interaction.

4.6 RESULTS

Results are provided as means with standard deviations. Each variable (Single Leg Stance Duration - left and right, Distance Walked, Steps Walked) was averaged across the three consecutive recorded trials. Separate 2 (group: SLA and HUM) $\times$ 2 (time: PRE and POST) mixed-design analysis of variance (mixed ANOVA) was performed. To match the requirements of the mixed ANOVA, all parameters were tested on normality with the Shapiro-Wilk test. Except for walking step performance in the POST measurement for the left and right legs, all data were normally distributed with $p > 0.05$. Additionally, the homogeneity of error variances was verified using Levene's test with $p > 0.05$ and the homogeneity of covariances was confirmed with Box's test with $p > 0.05$. With these assumptions met, a mixed ANOVA was conducted to examine interaction effects (assuming sphericity, as the group factor had fewer than three levels), global differences in the dependent variables between PRE- and POST-measurements, and potential differences between the SLA and HUM conditions. The level of significance was set at $p < 0.05$. Effect size was shown by using partial eta squared (η_p^2) and was defined as small for $\eta_p^2 \geq 0.01$, medium for $\eta_p^2 \geq 0.06$, and large for $\eta_p^2 \geq 0.14$.

The measurement results are presented in Table 4.2, while the analysis outcomes are summarized in Table 4.3. In the following sections, the results of the mixed ANOVA testing are reported separately for each condition as well as for the left and right leg.

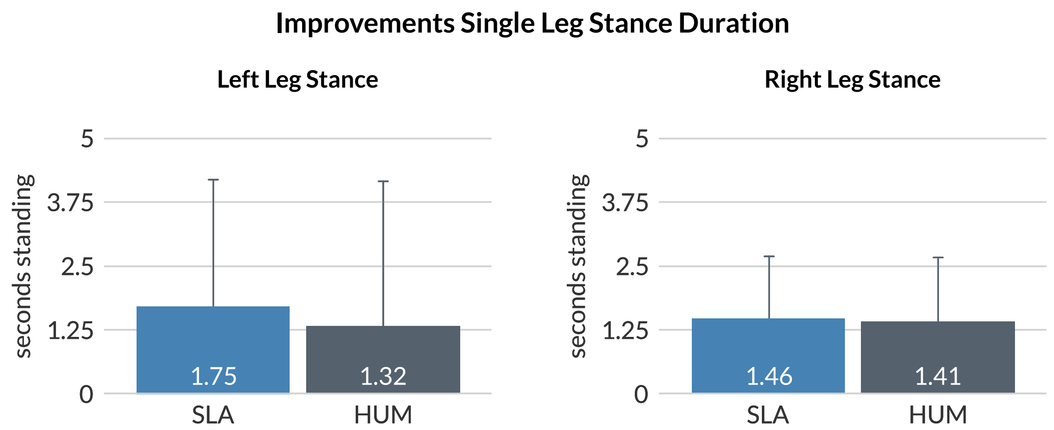

Figure 4.6: Improvements in seconds on standing on one leg on the slackline shown for both groups and both legs

4.6.1 *Single Leg Stance Performance*

No statistically significant interaction effect between time and group has been found, for the left $F(1.0, 10.0) = 0.0694$, $p = 0.798$, partial $\eta_p^2 = 0.007$ as well as for the right leg $F(1.0, 10.0) = 0.004$, $p = 0.950$, partial $\eta_p^2 = 0.000$. Since there was no significant interaction effect, the main effects will be reported.

There was no statistically significant main effect within-subjects for time (PRE to POST) for the left leg, $F(1.0, 10.0) = 3.843$, $p = 0.078$, partial $\eta_p^2 = 0.278$. However, a large statistically significant main effect within-subjects for time (PRE to POST) was found for the right leg, $F(1.0, 10.0) = 15.548$, $p = 0.003$, partial $\eta_p^2 = 0.609$.

No significant main effect between-subjects for group (SLA to HUM) has been found for the left $F(1.0, 10.0) = 0.009$, $p = 0.928$, partial $\eta_p^2 = 0.001$ right leg, $F(1.0, 10.0) = 0.008$, $p = 0.931$, partial $\eta_p^2 = 0.001$.

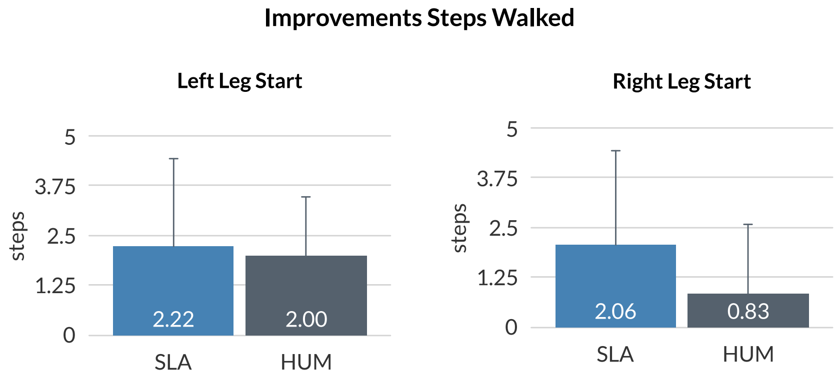

Figure 4.7: Improvements in number of steps being able to walk on the slackline shown for both groups and both legs

4.6.2 *Walked Steps Performance*

Although normality was violated for walking steps performance, mixed ANOVA is considered robust to moderate deviations from normality [23], particularly when sample sizes are balanced and variances are homogeneous. Therefore, the analysis was conducted under this assumption.

There was no statistically significant interaction effect between time and group, for the left ($F(1.0, 10.0) = 0.044$, $p = 0.838$, partial $\eta_p^2 = 0.004$) as well as for the right leg ($F(1.0, 10.0) = 1.039$, $p = 0.332$, partial $\eta_p^2 = 0.094$). Since no statistical significant interaction effect has been found, the main effects within the tests of within subject effects will be reported.

There was a large statistically significant main effect within-subjects for time (PRE to POST) for the left leg, ($F(1.0, 10.0) = 15.868$, $p = 0.003$, partial $\eta_p^2 = 0.613$) and also for the right leg ($F(1.0, 10.0) = 12.519$, $p = 0.005$, partial $\eta_p^2 = 0.367$).

No significant main effect between-subjects for group (SLA to HUM) was found for the left ($F(1.0, 10.0) = 0.753$, $p = 0.406$, partial $\eta_p^2 = 0.070$) and right leg ($F(1.0, 10.0) = 0.351$, $p = 0.567$, partial $\eta_p^2 = 0.034$).

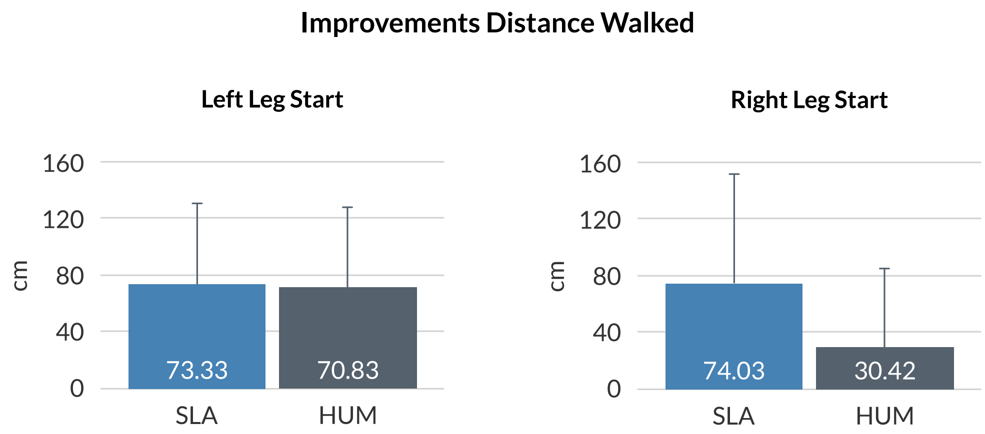

Figure 4.8: Improvements in distance in cm being able to walk on the slackline shown for both groups and both legs

4.6.3 *Walked Distance Performance*

There was no statistically significant interaction effect between time and group, for the left ($F(1.0, 10.0) = 0.006$, $p = 0.942$, partial $\eta_p^2 = 0.001$) or the right leg ($F(1.0, 10.0) = 1.235$, $p = 0.292$, partial $\eta_p^2 = 0.110$). Since no statistically significant interaction effect has been found, the main effects within the tests of within-subject effects will be reported.

In terms of within-subject time (PRE to POST) a large statistically significant main effect has been found for the left leg ($F(1.0, 10.0) = 18.563$, $p = 0.002$, partial $\eta_p^2 = 0.650$) and also for the right leg ($F(1.0, 10.0) = 7.082$, $p = 0.024$, partial $\eta_p^2 = 0.415$).

No significant main effect between-subjects for group (SLA to HUM) was found for the left ($F(1.0, 10.0) = 0.399$, $p = 0.542$, partial $\eta_p^2 = 0.038$) or ($F(1.0, 10.0) = 0.145$, $p = 0.711$, partial $\eta_p^2 = 0.014$).

4.6.4 *Rating of Exercise Difficulty*

After completing an exercise with both legs, participants were asked to rate the difficulty of each exercise on a 5-point scale, ranging from 1 (very easy) to 5 (very difficult). Figure 4.9 illustrates the average difficulty ratings for each exercise (blue line), along with a trend line representing a linear interpolation of the values (green line), and the standard deviation for each rating (gray bars).

	SLA		HUM	
	PRE	POST	PRE	POST
Stand Left (sec)	4.92 (1.80)	6.64 (2.60)	5.21 (2.25)	6.53 (1.65)
Stand Right (sec)	6.44 (2.02)	7.90 (2.33)	6.35 (2.92)	7.76 (2.16)
Steps Left	2.44 (1.26)	4.66 (1.53)	2.06 (1.00)	4.06 (1.56)
Steps Right	2.33 (1.05)	4.39 (2.00)	2.61 (1.48)	3.44 (0.89)
Distance Left (cm)	112.92 (35.90)	186.25 (43.25)	101.67 (28.46)	172.50 (63.94)
Distance Right (cm)	105.14 (25.30)	179.17 (66.65)	119.17 (56.86)	149.58 (36.13)

Table 4.2: Means and standard deviation results for Single Leg Stance Duration, Distance Walked, and Steps Walked in the Slackline System Group (SLA) and Human Trainer Group (HUM)

	Main Effect					
	Group x Time	η_p^2	Time	η_p^2	Group	η_p^2
Stand Left (sec)	p = 0.798	0.007	p = 0.078	0.278	p = 0.928	0.001
Stand Right (sec)	p = 0.950	0.000	**p = 0.003**	**0.609**	p = 0.931	0.001
Steps Left	p = 0.838	0.004	**p = 0.003**	**0.613**	p = 0.406	0.070
Steps Right	p = 0.332	0.037	**p = 0.005**	**0.367**	p = 0.567	0.034
Distance Left (cm)	p = 0.942	0.001	**p = 0.002**	**0.650**	p = 0.542	0.038
Distance Right (cm)	p = 0.292	0.110	**p = 0.024**	**0.415**	p = 0.711	0.014

Table 4.3: Interaction, time, and group effects on Single Leg Stance Duration, Steps Walked, and Distance Walked. While we could not show a significant difference in performance between groups, there was a statistically significant main effect when considering PRE- and POST-measures across both conditions.

The exercises were designed to increase in difficulty linearly. However, for the second level, a noticeable increase in perceived difficulty was observed in the first two exercises. Unlike the other exercises, 2.1 and 2.2 introduced sitting and balancing on the slackline for the first time, contributing to the higher difficulty. Exercises 2.3 and 3.1, as well as 2.4 and 3.2, differed only in the duration for which a pose needed to be held. Apart from these exceptions, the perceived difficulty generally followed the trend line.

4.6.5 *Semi-Structured Interview*

When asking for the general experience with the assigned training method, the outcome was similar for both groups. Participants reported positive learning progress during the training and expressed a sense of accomplishment from completing challenging yet manageable exercises, e.g. *"The exercises were well-framed. I felt a learning progress. At the beginning*

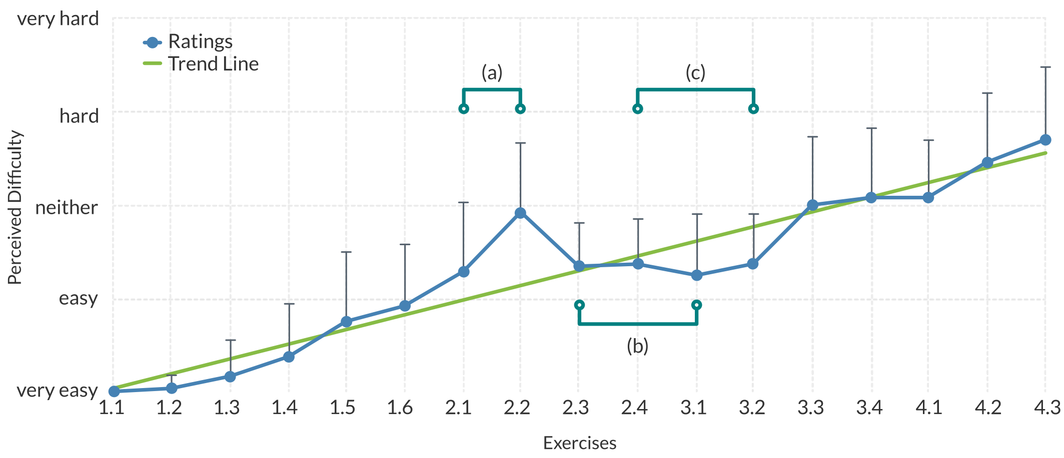

Figure 4.9: The averaged exercise difficulty ratings of the participants. Blue points represent averaged ratings per exercise, the green line indicates the trend line, and gray bars show the standard deviation. In exercisess 2.1 and 2.2 (a) participants had to sit on the slackline. Exercises 2.3 and 3.1 (b), as well as 2.4 and 3.2 (c) only differed in their duration.

I was not aware of the whole body balance but after the training, I could feel how the body balance changed and how I could keep my body's center of gravity." (HUM-10).

All participants who used the Slackline System appreciated the environment design, the clear instructions, the looping exercise videos, and the timely, appropriate feedback provided during execution. *"I liked the user view because you can see how you act by yourself. It is also positive that I can use the system without any further help."* (SLA-P6). *"[...] There is no need to watch YouTube tutorials with such a system. It displays all relevant information and provides appropriate feedback"* (SLA-P3). However, it was noted that a personal trainer might be more beneficial in providing specific advice on aspects that the Kinect system could not detect (SLA-P4, SLA-P6).

Participants using the Slackline System reported enjoying the training and having fun interacting with the system. They were also motivated to complete the current exercise in order to unlock the next one. The checklist seen in Figure 4.3 on the left was highlighted as a very useful feedback indicator. Additionally, participants identified a variety of application scenarios for the interactive training system. Most frequently mentioned were physical therapy, rehabilitation, training for sports activities, gyms, and home training.

4.6.6 *Observations*

During the PRE measurement, all participants showed little control over their bodies while standing or walking on the slackline, displayed by their seemingly involuntary swaying and frequent stepping off the slackline. Additionally, many attempted to walk quickly across it.

In contrast, participants showed noticeable improvements during the POST measurement after the training. Each participant demonstrated better control, standing and walking slowly on the slackline with a visibly increased body control.

On a technical site, there were a number of limitations related to the tracking quality of the Kinect that were revealed during study execution. First, the general tracking performance of the Kinect was influenced by participants' clothing color (e.g., black clothing absorbed the Kinect's infrared light, leading to tracking issues). Second, the movement detection was suboptimal for certain exercises. For instance, exercises involving sitting on the slackline occasionally caused the system to misidentify the legs, sometimes recognizing the slackline itself as a leg. Third, stepping onto the slackline also led to tracking problems. When participants placed their outer leg too close to the slackline while stepping up, the Kinect often failed to track it correctly. As a result, the exercise recognition occasionally produced false negatives, where correctly performed movements were not recognized by the system.

4.7 DISCUSSION

Our analysis did not reveal any statistically significant differences in performance between participants in the Slackline System Group and the Human Trainer Group. Therefore, based on the results of this study, we were unable to demonstrate that people learn better (or worse) using the Slackline System compared to traditional human-led training. As shown in Figure 4.6, Figure 4.7, and Figure 4.8, participants using the Slackline System performed slightly better overall. However, these measures also showed a large standard deviation. A large difference can be observed in Figure 4.7 and Figure 4.8 showing the walked steps and walked distance performance differences for starting with either the left or right leg. Here, participants training with the Slackline System showed a visibly larger performance of the left leg compared to the right leg. Nonetheless, these results also display a high standard deviation and, therefore, are not statistically significant.

Overall, we could not show a siginificant difference in performance between the two groups. This outcome could be attributed to several factors. Firstly, the training duration may have been too short to yield statistically significant differences between the groups. Secondly, all participants were only taught basic slacklining techniques (i.e. standing and walking on the slackline), with no advanced skills introduced. To teach more complex exercises and techniques, the quality of instruction and feedback during execution becomes crucial, as these elements are key to understanding how an exercise works and how to perform it correctly. Consequently, incorporating more advanced exercises and extending the training period could potentially yield to more pronounced differences between groups.

Secondly, we did not assess and account for the general balance skills of the participants. Subjects were selected based on their lack of slackline experience and absence of specialized balance skills from specific sports activities. The results showed a large standard deviation in all measured variables. This variability is likely due to participants improving at different rates during the training in either group. Furthermore, differences in individual balancing skills and abilities possibly contributed to this outcome. Recruiting a larger sample size could have helped mitigate this effect.

The slightly better, though still not significant, performance difference between the groups may be attributed to the recognition system of the Slackline System. While the system allowed some leeway in determining whether an exercise was performed correctly, the human trainer might have been more lenient toward deviations from perfect movement execution. This could have resulted in more repeated trials for participants in the Slackline System Group, as the system "forced" them to repeat movements until they met the quality threshold.

4.7.1 *Time Effects*

As we could not demonstrate a significant performance difference between the two groups, we analyzed performance changes from the PRE- to POST-measurement. Most measures showed significant differences from PRE to POST across both groups (see *Time* column in Table 4.3). All participants improved across all measures except for the single-leg stance duration on the left leg. This exception may be attributed to the fact that all participants reported their right leg as dominant.

The general improvement in other measures, however, suggests that the training exercises used in both groups were effective and contributed to the participants' learning progress.

4.7.2 *Slackline System Group vs. Human Trainer Group*

Although the measures from participants using the Slackline System were numerically slightly better than those training with the human trainer, the difference was not sufficient to reach statistical significance. Both groups received the same exercise structure, instructions, repetitions, and time requirements for holding each exercise. The only difference was in how the information and feedback were delivered during the exercises. It is possible that both training methods provided a comparable amount of information and feedback, resulting in neither group having a distinct advantage. Consequently, the group effects were similar. This suggests that both training methods yield comparable outcomes and can be effectively compared with each other.

4.7.2.1 *Exercise Difficulty*

As mentioned earlier, the exercises and their requirements were designed to increase in difficulty linearly. As illustrated in Figure 4.9, the perceived difficulty generally followed the trend line, with a few notable divergences.

The first two exercises of the second level (2.1 and 2.2) were perceived as disproportionately more difficult. This may be due to these exercises introducing balancing on the slackline while sitting for the first time. Additionally, exercises 3.1 and 2.3, as well as 3.2 and 2.4, received similar perceived difficulty ratings. This similarity can be attributed to the fact that these exercises only differed in the duration participants were required to hold a specific pose. This minor variation may have led to comparable difficulty perceptions.

Overall, these findings validate the appropriate integration of the implemented exercises as a training model for beginners on a slackline.

4.7.2.2 *Observations and Semi-Structured Interviews*

Participant feedback indicated that the virtual environment created a playful and engaging training experience. The level system encouraged participants to complete the current exercise to revel the upcomming ones. Despite the tracking issues of the Kinect, all participants enjoyed training with the system.

The user interface in the training mode, especially the checklist and timer were praised as effective feedback tools. These feedback elements helped participants align their bodies correctly and understand how to change form to imrpoved their movements. Immediate feedback on errors and successful repetitions further enhanced motivation.

The sitting exercise, perceived as particularly difficult, may benefit from being replaced with an easier introductory exercise to help participants build confidence. Overall, participants found the exercises well-structured and perceived a learning progress. The system's playful environment and challenging tasks motivated them to achieve their goals. All participants expressed enjoyment in using the interactive slackline system and recommended it for beginners interested in slacklining.

4.8 LIMITATIONS & FUTURE WORK

We found a relatively large standard deviation in the PRE- and POST-measurements. This might be an indication for different levels in (balance) skill within the participants. A future system might take this differences into account and adapt the exercises or requirements accordingly. While participants already like the playful design of the environment, further gamification elements could improve the enjoyment and adherence even more. Since we could not find a significant difference betweens groups, recruiting more participants in future studies could be worthwhile.

4.9 CONCLUSION

In this chapter, we investigated the design and implementation of an interactive slackline training assistant. The system was implemented using a slackline facing a large projection and a Kinect v2. In a user-study, we compared learning basic slackline skills (e.g. walking on a slackline) using the slackline training system to the classical approach of a human trainer. While we could not show a significant difference between the two groups, both showed significant improvement in performance from the beginning to the end of the training. Observations and semi-structured interviews indicate that the enjoyable game environment gives a playful character to the training situation and the challenging exercises motivated the participants to reach their goal of accomplishing the exercise. These findings suggest that an interactive slackline trainer can serve as an effective alternative for autonomously learning the basics of slackline training. Given that the participants felt motivated by the system, we propose further investigations regarding the use of a gamified approach in balance training.

4.10 CONTRIBUTIONS TO THE RESEARCH QUESTIONS

This work contributes to the research questions **RQ 1**, **RQ 2**, and **RQ 3**.

What are factors influencing the acceptance and willingness of athletes to use a computer-supported assistive system for sports training?

RESEARCH QUESTION 1 Findings from the semi-structured interviews suggest that a structured and iterative learning schedule with clear outcomes can motivate users to continue training. This was achieved by only allowing participants to progress once an exercise was mastered. Such an iterative approach likely prevents trainees from feeling overwhelmed by introducing complex movements too quickly. Furthermore, offering trainees autonomy by enabling training at their convenience - without the need to adhere to fixed appointments with a personal trainer or group - emphasizes the benefits of assistive systems. Additionally, a playful user interface has shown to increase enjoyment, which could maintain user engagement.

What are effective methods for tracking and assessing movements to inform real-time feedback development and testing in a sports context?

RESEARCH QUESTION 2 In this work, the Kinect v2 was employed to track the trainee's body movements. Instead of developing a custom recognition method, the Kinect SDK's gesture recognition system was adapted for the sports context. This allowed specific movements in slackline training to be broken down into manageable chunks of motion. When combined with rule-based techniques, this approach enables the implementation of interactive systems with relative ease. Thus, this work contributes to **RQ 2** by demonstrating an unobtrusive method that allows researchers to rapidly prototype and iterate systems investigating feedback methods without relying on "wizard-of-Oz"-style recognition.

How could computer-supported assistive systems communicate feedback and instructions to athletes during training?

RESEARCH QUESTION 3 Finally, this study contributes to **RQ 3** by showcasing how various feedback elements can deliver immediate, actionable feedback. In this system, feedback was presented in form of a large projected screen in front of the user. Especially in slacklining this method is suitable since because one basic instruction in the sport is to focus on a point ahead of the athlete [213]. This setup ensures that feedback integrates seamlessly into the athlete's line of sight without overly disrupting their balance or flow. When designing the feedback, we paid attention that the visualizations would be perceivable despite the visual focus to the front. A progress bar showed the overall quality of the movement being performed, thus providing a way to self-validate the current performance. More detailed information was available in the form of a checklist with important aspects of the specific movement (e.g. left leg stretched). This binary feedback allowed the users to receive concrete feedback on demand to improve performance. Using this kind of quick and easy to perceive actionable feedback is likely suitable for other training scenarios that employ a magic-mirror metaphor (see Section 3.2). Examples for such system have been presented in the past in the context of rehabilitation [60, 218] or other sports like martial arts [46, 93, 94], dance [10, 55], or general movement learning [139, 249].

5 INVESTIGATING PERCEPTION AND ACCEPTANCE OF WEARABLES IN ROCK CLIMBING

While the previous chapter addressed slacklining, this chapter and the following ones focus on the sport of rock climbing. Unlike slacklining, where the degrees of freedom are more limited and attention is typically directed forward, rock climbing allows athletes to move in any direction, pause, reorient, and continue. This broader range of motion and the necessity to plan and execute movements accordingly present greater opportunities for interactive systems to provide feedback. This chapter contributes to **RQ 1** and **RQ 3** by focusgosing on real-time feedback with a low information content. Most content of this chapter was previously published under the following publication.

Felix Kosmalla, Frederik Wiehr, Florian Daiber, Antonio Krüger and Markus Löchtefeld. "Climbaware: Investigating Perception and Acceptance of Wearables in Rock Climbing". *In: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems.* CHI'16, USA [133]

5.1 INTRODUCTION

Rock climbing in its original form was only practiced by smaller, more adventurous groups of people who gained expertise in handling the necessary protection equipment such as ropes and bolts while climbing outdoors (see Section 3.3.1). Today, climbing has become a very accessible sport gaining in popularity, both being practiced indoors and outdoors. While in 2014 there were 353 climbing and bouldering gyms [98] in the United States, this number almost doubled in 2024 to 635 commercial climbing gyms [37]. Even though indoor climbing on artificial walls and plastic was initially thought as a form of training for climbing outdoors, many people only engage in this form of climbing because it is easily accessible and does not depend on weather conditions. As opposed to outdoor climbing, the climber is able to leave work and go straight to the climbing gym, since little to no preparation is needed. Often, harnesses, shoes and ropes can be rented.

High security standards [228] for the walls and the equipment, as well as mandatory introductory courses provide a safe exercise environment for all age groups. Furthermore, climbing is a sport which demands, but also fosters, both physiological and psychological strength. During a climb, the climbers use numerous muscles in their body while simultaneously concentrating on their next move, grabbing a tiny hold and paying particular attention where to place their feet, in which direction to shift their center of mass, and how to balance on a small ledge serving as a hold for their feet.

The factors discussed above outline how different climbing is from other sports such as running or cycling. It represents a more holistic activity that, in addition to muscle force and technique, demands a high level of cognitive effort from the climber [86]. If we now consider a climbing training system that aims at giving the climber feedback in-situ as proposed in related work e.g. ClimbAX [140], we need to take the cognitive capabilities of the climber into consideration. If we want to give appropriate feedback to the climbers about their performances or how they should adapt their technique during a climb, such a system needs to be well tailored to these capabilities. Finding suited notification channels and positions for devices to deliver the feedback is a crucial aspect. For example Roumen et al. [191] showed that a simple task like walking has a significant influence on the perceivability of different feedback channels. We expect these effects to be even more prominent for a complex activity such as climbing.

In this work, we investigated whether and how a climber can perceive and distinguish notifications, which are sent out from a device worn on her body, even with the high cognitive load described above. Existing interaction concepts that are widely used in other fields, such as sport watches, do not necessarily meet the specific requirements of climbing. We conducted an online survey in which we assessed appropriate body parts on which to place a wearable device and possible notification channels. Based on these results we developed a wrist worn device which was able to notify the user with either vibration or visual cues. In addition to that, we used bone conducting headphones for audible cues and tested all three notification channels in a user study in a local indoor climbing gym using top-rope routes. We propose exemplary use cases for different communication channels based on the findings of the user study.

While parts of the study described below are very specific to rock climbing, we believe that it can inform the design of wearables for activities where high physical and mental demand come together such as white water kayaking or windsurfing.

5.2 BACKGROUND AND CONTEXT

The investigations presented in this chapter are related to previous studies on (1) wearable devices, (2) the influence of mobility and (3) climbing research in HCI as outlined in Section 3.3.1.1.

5.2.1 *Wearable Devices*

A variety of different wearable devices have been investigated in the past. In the following, we will briefly discuss a subset of these that have the potential to be used during climbing.

So far most of the related work in this area focused on input techniques and only few investigated the output capabilities in depth. When it comes to interaction with wearables, Profita et al. [185] found the wrist and the forearm to be the most socially acceptable area for such devices. While their study mainly focused on interaction, Harrison et al. [96] investigated reaction time to visual alerts. They found that reaction time performance is not only influenced by the location but also dependent on outside factors such as occlusion. In a climbing scenario, these factors will be even more prevalent compared to everyday interaction with wearable devices. Especially the position of the wrist on the complete frontal plane of the climber.

While most of the prior work mainly focused on input on such devices, the limited size makes output complicated as well. One of the earliest interactive wrist-worn devices has been developed by Hansson and Ljungstrand [95]. Their Reminder Bracelet allowed a connected PDA to notify the user with the assistance of integrated LEDs. Williams et al. presented a wearable ambient display that allowed for semi-public notifications using LEDs as well [238]. Pasquero et al. investigated tactile output on a smartwatch [178]. Besides notifications, they found it to be suitable for obtaining numerical data as well. All of these works have only been tested in well-structured and controlled lab settings.

The multiple display segments of the Facet system [146] were able to overcome the problems that arise from the small display size of current devices. On the one hand, the multiple viewing angles allowed for different relative head positions while the ability to stretch applications over multiple display segments reduced the effect of the small display size. Nevertheless, the system not only requires a high amount of hardware but also relied on manual adaption which might not be possible during climbing.

5.2.2 *Influence of Mobility*

When interacting with mobile devices, mobility is an important factor and often neglected in favor of non-mobile lab studies. For example, when walking, users can only keep stable interaction performance at 74% of their preferred walking speed [20]. Furthermore, the effect of encumbrance on interaction - carrying an object in one hand and interacting with the other - while for example walking, has a significant influence on task performance for target acquisition on a touchscreen mobile phone [165]. During climbing people are not only carrying an object but also often have no free hands since they are grabbing at least one hold at a time to prevent them from falling off the wall.

Roumen et al. [191] investigated wearable interactive rings regarding the perceptibility of different notification channels (light, vibration, sound, poke, and thermal) during five levels of physical activity (laying down, sitting, standing, walking, and running). According to their results, vibration is the most reliable and fastest notification channel, followed by poke and sound independent of the level of physical activity. The other two channels, light and thermal, were less noticeable and were affected by the level of physical activity.

Notifications on a wearable add a secondary task to the main task of climbing. This relates to cognitive aspects of how such a secondary task might influence the climbing performance. Green and Helton explored the influence of a memory task on climbing efficiency [86]. They found that climbing efficiency was significantly impaired through the memory task. Helton et al. [99] followed up these results and their findings indicated that climbing is highly cognitively demanding. Based on their results and memory resource theory, they suggested the need for communication equipment that augments the climber's memory. They suggest using visual or tactile modalities but did not investigate their effectiveness. By the time of publication, to the best of our knowledge, the effects of climbing on the perception of different output modalities have not been investigated. We are following up on the work of Helton et al. and are investigating these in a real world setting.

5.3 ONLINE SURVEY TOOL

To gain initial insights into possible locations for wearables, we conducted an online survey. Besides general questions about demographics and climbing specifics, we asked participants to rate various body positions based on aspects such as appropriateness and perceivability of different notification cue modalities. To facilitate this assessment, we developed a custom online tool that participants could use independently. While this tool was specifically designed for the rock climbing use case, it can be easily adapted for other sports contexts to gather early user feedback. The tool combined general questionnaire functionalities to collect demographic and other data with a custom interface that allowed for a flexible assessment of different aspects of body parts.

The core of the online tool is an interface that displays a silhouette of a person with predefined body positions, as shown in Figure 5.1. Within this interface, participants were given instructions specifying the factor by which each body part should be assessed. In this case, participants were asked to evaluate each body part on how appropriate it would be to wear a device on that position during climbing, using a five-point scale ranging from "not appropriate at all" to "fully appropriate."

A wizard guided participants through all predefined body locations, with a green indicator showing which body positions had already been assessed. After completing the predefined body parts, participants were asked whether they wanted to add custom body parts beyond the predefined ones (see Figure 5.2).

After assessing the body parts based on how appropriate it would be to wear a device at these body positions, the next screen asked participants to estimate how perceivable a notification originating from each body position would be (see Figure 5.3). In this study, participants rated body parts across three different modalities: tactile, visual, and auditory.

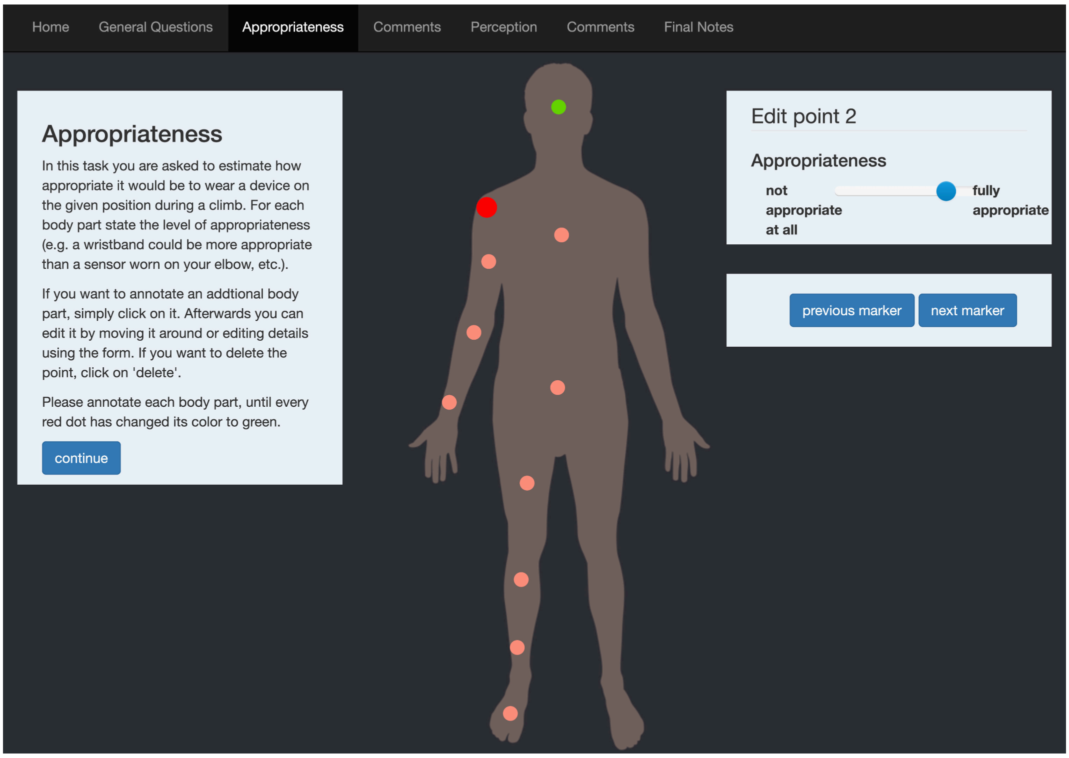

Figure 5.1: Online tool to assess different aspects of body parts. Here, the appropriateness of a wearable device placed at the body positions indicated by the points on the silhouette can be set by participants.

For each body part, three sliders allowed participants to adjust their estimates of the perceivability of each modality originating from that specific body part, on a scale from *'not perceivable at all'* to *'very perceivable'*.

5.4 RESULTS OF THE ONLINE SURVEY

In the following, we will describe the results of the online survey. We will start with a report of the general question and go forward from that with the analysis of the body part assessments by the participants.

5.4.1 *General Questions*

54 climbers participated in the survey, of which 11 were female. When asked about their climbing skill, 29 considered themselves beginners, 18 intermediates, and 7 expert climbers. The age of the participants ranged from 18 to 49 with an average age of 27.87 years ($SD = 7.7$). We asked the participants to state whether they would rather boulder (1) or do classic rope climbing (5) on a 5-point likert scale. On average the participants answered 2.7 ($SD = 1.05$), which means that the participants would rather boulder than climb. For

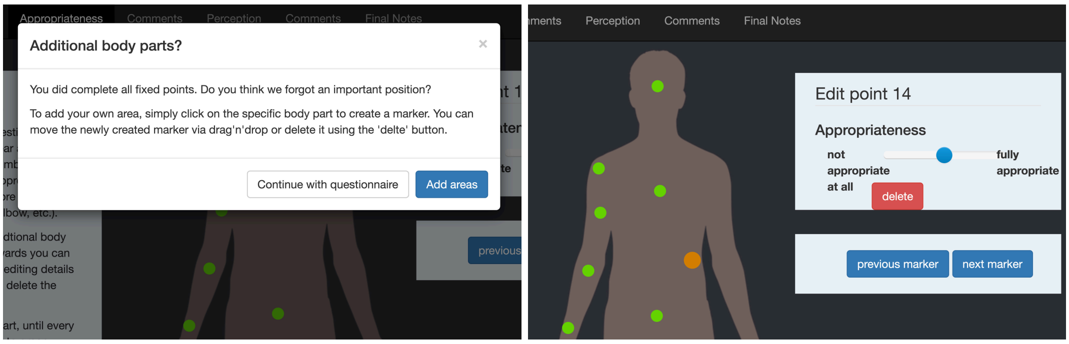

Figure 5.2: To collect more body positions, participants were encouraged to add more body positions if seen fit. These custom body positions could be removed or relocated at will.

both disciplines the participants had to state whether they train outdoors (1) or indoors (5). On average the participants answered with 1.89 $(SD = 1.66)$ for bouldering and 1.63 $(SD = 1.36)$ for climbing. This shows a tendency for practicing both, climbing and bouldering, outside on a real rock.

5.4.2 *Assessment of Body Positions*

After the general questions, participants were asked to assess different body locations, beginning with rating how appropriate a body position would be to wear a device there.

Appropriateness

Body Position	**Mean (SD)**
Wrist	3.57 (1.46)
Upper Arm	3.30 (1.30)
Ankle	3.26 (1.22)
Upper Leg	3.19 (1.28)
Chest	3.13 (1.22)
Lower Arm	3.09 (1.39)
Head	3.06 (1.31)
Waist	2.98 (1.25)
Shoulder	2.60 (1.29)
Lower Leg	2.52 (1.24)
Foot	2.39 (1.51)

Table 5.1: Averaged ratings of body positions assessing appropriateness when wearing a device on this position. (1) not appropriate at all, (5) fully appropriate

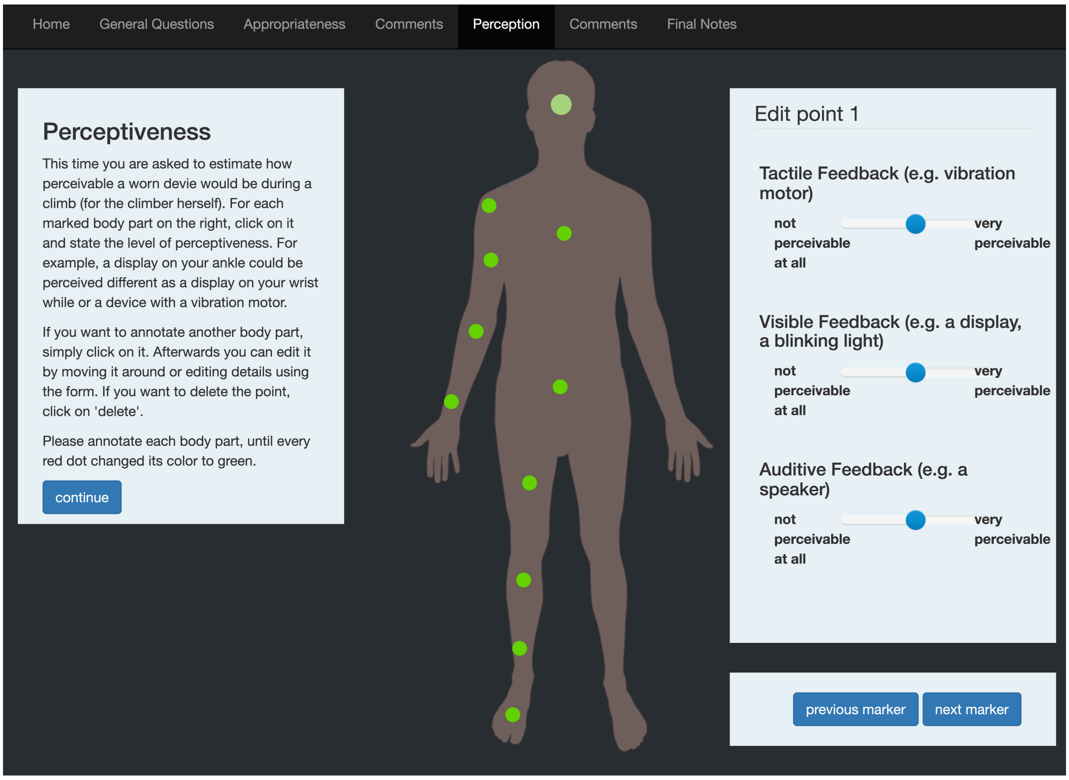

Figure 5.3: For each body position, participants were asked to estimate the perceptiveness of tactile, visual, and auditive notifications originating from this body position.

5.4.2.1 *Appropriateness*

In the second part of the questionnaire which assessed the appropriateness, the participants were asked to state how appropriate or inappropriate a device would be when worn during a climbing session. Using the online tool described above, we selected eleven points on the body to be assessed: head, shoulder, chest, upper arm, lower arm, wrist, waist, upper leg, knee, and ankle. Except for the head, chest, and belt area all points where located on the right half of the body for the sake of simplicity. For each body part, the participant could choose a value from *(1) not appropriate at all* to *(5) fully appropriate*. A visualization in form of a heatmap of the body parts and their averaged values for the appropriateness can be seen in Figure 5.4 at the top left. As it can be observed, the wrist, upper arm, and ankle were deemed as the most appropriate places on the body. Table 5.1 gives detailed information about the placements at each body part. For this, we summed up all the answers given by the participants for the given body parts. The feet, lower leg, and shoulder area were assumed as least appropriate.

After the assessment of the appropriateness per point basis, the participants were asked which of the body parts they would consider most suitable for which kind of device and if they could think of concrete examples. Answers were given in a text field and analyzed as follows. The wrist (named 20 times) was clearly in the top position for appropriateness,

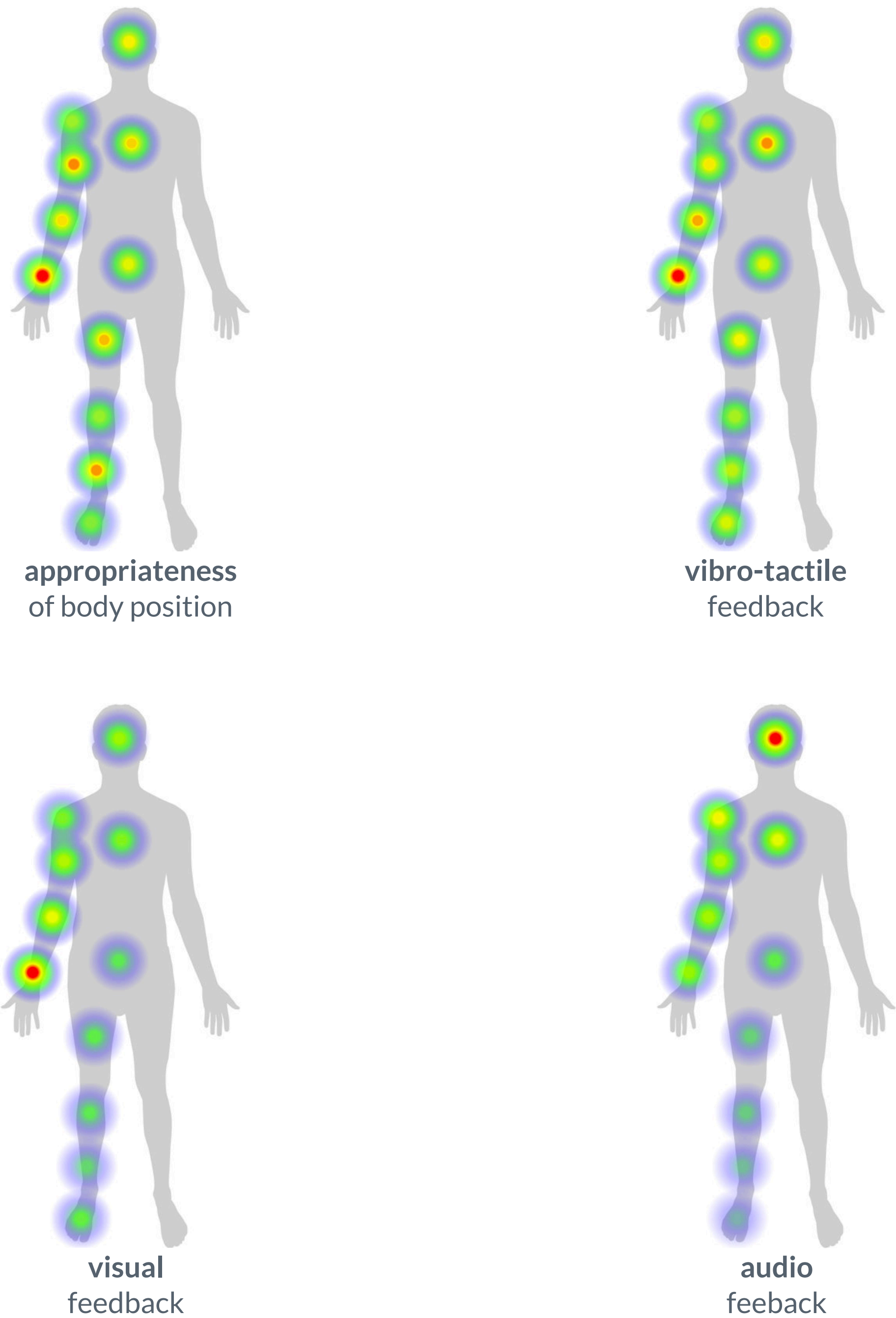

Figure 5.4: Results of an online study evaluating the appropriateness (top left) of wearable devices for different body positions and the estimated perception quality of tactile (top right), visual (bottom left), and audio cues (bottom right) rendered by those devices. Redder areas indicate higher perceived appropriateness or cue perception quality.

followed by the upper arm (8), chest (7), ankle (6), head (6) and waist (4). When asked for inappropriate positions, the joints in general (named 8 times), head (7), feet (5), legs (4), hands (4), and shoulders (2) were mentioned as unfavorable position choices.

Some participants also mentioned preconditions for possible body worn devices. The most important requirement for such devices was that it would not hinder the climbing movements and the climbers' flexibility at all. Especially the joints and the surrounding areas were rated as very inappropriate. Another concern of the participants was the risk of injury. The participants feared that devices placed on exposed body parts like knees, elbows or legs, are prone to get tangled somewhere on the rock or the artificial climbing wall and either damage the device or may lead to injuries on the climber herself. A common understanding was that a device worn on the wrist would be the most appropriate, since people are already accustomed to smartwatches or bracelets in general. The device should be thin and neither limiting motion nor being uncomfortable.

Followed by the assessment of appropriateness, the participants were asked to estimate the perception quality of the three output channels, vibration, light, and sound. For this, the participants had to state for each channel how perceptible a notification triggered from a device, worn at a specific body position, would be. The participants could answer this question by selecting a point from a five-point scale ranging from *(1) not perceivable at all* to *(5) very perceivable.*

Tactile Notifications

Body Position	**Mean (SD)**
Wrist	4.09 (0.99)
Chest	3.76 (1.12)
Lower Arm	3.69 (1.10)
Head	3.54 (1.52)
Upper Arm	3.52 (1.03)
Upper Leg	3.46 (1.24)
Waist	3.33 (1.15)
Foot	3.30 (1.30)
Ankle	3.15 (1.28)
Shoulder	3.09 (1.34)
Lower Leg	3.00 (1.26)

Table 5.2: Averaged ratings of body positions when estimating perception of tactile notifications. (1) not perceivable at all, (5) very perceivable

5.4.2.2 *Perception of Tactile Notifications*

We asked the participants to state how perceivable a vibro-tactile notification would be when triggered during climbing at the given body positions. Figure 5.4 (top right) shows a visual interpretation of the results. It can be observed that the perceptiveness of vibro-tactile notifications is estimated slightly higher in the upper body half than in the area below the waist. Table 5.2 summarizes the answers for tactile notifications; While the wrist, chest, and lower leg area were estimated as the most perceivable areas, the lower leg, shoulder, and ankle were estimated as the least perceivable points to place a tactile notification device.

Visual Notifications

Body Position	Mean (SD)
Wrist	3.89 (1.21)
Lower Arm	3.24 (1.12)
Upper Arm	2.91 (1.16)
Head	2.80 (1.64)
Chest	2.56 (1.33)
Shoulder	2.52 (1.23)
Foot	2.28 (1.30)
Upper Leg	2.19 (1.07)
Lower Leg	2.11 (1.17)
Waist	2.11 (1.20)
Ankle	1.96 (1.00)

Table 5.3: Averaged ratings of body positions when estimating perception of visual notifications. (1) not perceivable at all, (5) very perceivable

5.4.2.3 *Perception of Visual Notifications*

Next, we asked the participants to estimate how they think visual notifications would be perceived at each of the eleven body parts during climbing. As it can be seen in Table 5.3 and Figure 5.4 (bottom left), the body areas with the highest estimated perception of visual notifications are all located on the arm (wrist, lower arm, upper arm), while the area with the least estimated perception are the ankle, lower leg, waist, and upper leg.

5.4.2.4 *Perception of Audible Notifications*

Finally, we asked the participants how audio notifications would be perceived from the respective body parts. In contrast to the output channels: vibro-tactile and light, audible notifications are clearly estimated to be the highest around the head area (see Figure 5.4, bottom right). Body parts located further from the head are scored with a low perception of audible notifications. Looking at Table 5.4 reveals a descending order of body parts, beginning at the head and ending at the foot, confirming the observations made on the heatmap.

5.4.2.5 *Qualitative Feedback to the Output Modalities*

As in the *appropriateness* section of the questionnaire, the assessment of the estimated perception of notifications at different body positions was followed by a summarizing

Audio Notifications	
Body Position	**Mean (SD)**
Head	4.17 (1.08)
Shoulder	3.56 (1.17)
Chest	3.44 (1.15)
Upper Arm	3.19 (1.20)
Lower Arm	3.04 (1.07)
Wrist	2.93 (1.25)
Waist	2.33 (1.15)
Upper Leg	2.06 (1.04)
Lower Leg	2.00 (1.04)
Ankle	1.83 (0.98)
Foot	1.67 (1.04)

Table 5.4: Averaged ratings of body positions when estimating perception of audio notifications. (1) not perceivable at all, (5) very perceivable

question. We asked participants which body positions they believed would be easier to perceive notifications than others. The wrist, with 19 mentions, topped the list of positions considered good for triggering notifications, followed by the head (9) and arms (8). In contrast, the feet (7), legs (4), and ankles (2) were perceived as less effective positions for notifications. In general, participants agreed that the head is the most suitable position for audible notifications, as the distance between the audio source and the ears is shortest, particularly when using devices like smart glasses. Additionally, most participants stated that both visual and vibro-tactile notifications would be most effective on positions on the arms, especially the wrist. Regarding visual feedback, participants emphasized that the device must be in the line of sight, which favors placement on the arms. *"The arms and hand are closest to the ear and eyes since I am mostly looking upwards when climbing rather than downwards." (P13)* In contrast, all participants agreed that areas on the lower body, except some tactile notifications, are not well-suited for any type of notification.

5.4.3 *Preliminary Design Implications*

The feedback of the participants can be generalized as follows:

1. Audio feedback is most suitable around the head.
2. Tactile feedback is most suitable on the arms.
3. Visual feedback should be in the line of sight.

4. The wrist is most suitable for a device that combines the two channels light and vibration.
5. A body worn device should be durable, not obstructive, and not entail any risk of injury.

These results are in accordance with former studies that identified the wrist as the body location at which notifications were perceived the fastest. In particular, this has been shown for the notification with visual cues during other motor activities in which the wrist was located in the immediate field of view, such as reading, writing, typing, and conversational gesturing [96].

5.5 PERCEPTION STUDY

We used the insights from this online survey to inform the design of a study apparatus that would allow us to test different notification modalities that could be used during a rock climbing ascent. Our goal was to test whether climbers would perceive visual, audio, and tactile notifications differently when climbing an easy route, versus climbing a hard route.

5.5.0.1 *Apparatus*

Figure 5.5: Implemented wrist-worn notification device, delivering visual and tactile notifications (left). Bone conducting headphones delivering audible notifications (right).

Based on the findings above, we opted to use a wrist-worn device to deliver visual and tactile notifications. To address participants' concerns about the risk of injury, we designed a wristband with a magnetic latch that opens automatically if the device becomes tangled during climbing. For audio notifications, we utilized bone-conducting headphones, which allow climbers to remain aware of their surroundings while receiving notifications.

We conducted the study in a local climbing gym, where we picked two top-rope routes of differing difficulty. This kind of route ensures the safety of the climber since the rope runs through a fixed anchor at the top of the route and does not require any additional self-protection except for tying herself in properly. Both routes were approximately 12 meters high.

Based on the guidelines presented above, we designed a wrist worn device which consists of a microcontroller (RFDuino) with integrated bluetooth capability and three RGB LEDs, which were able to emit *red*, *orange*, and *green* light (see Figure 5.5, left). We used LEDs which emitted light that could be perceived in even bright conditions. Furthermore, a battery and a vibration motor were included to provide vibro-tactile notifications to the user. An off the shelf 3V vibration motor was used with a vibration amplitude of $0.8G$, which is comparable to smartwatches like the Samsung Gear. With this it was possible to induce vibrations of arbitrary length and pattern, as also flashing or solid lights in various colors and brightnesses. We used the approach of a custom designed device as opposed to a smartwatch because it gives the user a feeling of a more abstract device. A potential bias may occur when using a smartwatch but is therefore counteracted with the use of the device. To meet the need for safety and injury prevention which arose during the online study, we equipped the wristband with a magnetic latch. The latch is strong enough to hold the device in place, but is sufficiently fragile to open if the wristband was caught during the climb, preventing injury by the wristband in the event of a sudden, unlucky fall. In addition to this device, we used a pair of AfterShokz BLUEZ 2 bone conducting headphones for audio notifications (see Figure 5.5, right). With these headphones, we played back sound chimes with frequencies that ranged from $500Hz$ to $20,000Hz$ We chose these headphones because they do not cancel out the climbers from their surrounding, enabling them to hear both the audio notifications and commands from their belayer. The latter is a crucial prerequisite for a safe execution of sports climbing. To control both notification devices, an Android application was developed to manually trigger notifications to either the wrist-worn device or the headphones.

5.5.1 *Method*

5.5.1.1 *Participants*

12 climbers (1 female) participated in our user study. Their age ranged from 13 to 60 years, with an average of 34.58 $(SD = 11.74)$ years. For participants under the age of 18 we got written permission from their parents or legal guardians that they were allowed to participate in our experiment. When asked for their climbing skills, seven participants stated to climb *not harder than 5.11*, and five claimed to climb routes rated *5.12 and up*. The difficulties used in the results above are reported in the *Yosemite Decimal System*[1]. As an example, climbing beginners should be able to climb a route graded with 5.4, while professional climbers succeed in routes graded with 5.15. None of the climbers of the perception study participated in the online survey.

1 http://climber.org/data/decimal.html

5.5.1.2 *Conditions*

We tested three different notifications channels that could be perceived by the participants (light, vibration, sound). The first condition consisted of a visual cue, emitted from three RGB LEDs in the colors *red*, *orange*, and *green* for four-seconds. A vibro-tactile cue in form of a one-second long vibration pattern was used as the second condition. The vibrational pattern consisted of either one vibration for one-second, two vibrations within one-second, or three vibrations within one-second. The third cue was an audio signal which also lasted for one-second and consisted of a tone, either played once, twice, or three times. All notifications were manually triggered with the help of a smartphone app, operated by the experimenter.

5.5.1.3 *Tasks*

When climbing, the climber undergoes both physical and psychological stress. The difficulty of a route depends on how hard it is to keep a steady grip of the holds, which body positions are enforced, how hard it is to balance, and depending on the climbers' attitude, the fear of falling. To investigate the perception in the presence and absence of stress, we selected two different routes. Route *R1* had a difficulty of 5.7 and was equipped with holds which where relatively easy to grab. The second route, *R2*, was picked as the hard route with a difficulty of 5.10c, was slightly slanted and consisted of many holds with a large slope, thus making them hard to grab. The task for the participants was to climb both routes and to report notifications and their levels as soon as they noticed them (e.g. saying "red" when testing the visual channel, and e.g. "two" for tactile and audible notifications).

5.5.1.4 *Design*

We designed the experiment so that (1) each order of routes (easy route first, then hard route and vice versa) was climbed by the same number of participants, and (2) each of the six possible orders of notification channels were tested. For two consecutive climbs (easy and hard), only one channel was tested. This resulted in six climbs which each participant had to ascent. To avoid ordering effects, the order of each condition of the tasks was latin square counterbalanced between participants.

5.5.1.5 *Procedure*

First, the participant was given an explanation of the experiment and was asked to sign an informed consent to record the data and video capture the study. In the event of participants under 18, parents or legal guardians were asked for consent. Then while still standing on the ground, we demonstrated the different notification channels and their corresponding levels. Before the first climb, we asked the participants to fill out an initial questionnaire asking for their age and climbing experience. Depending on the current iteration, the participant started with the easy or hard route and with one of the three notification channels. During the climb, we triggered three notifications in three different levels, where each level was triggered once and in a random order per route. We chose three distinct holds in each route where the participant had to use each of these holds during the ascent. For the hard route, we picked the first hold so that the resulting body position was especially strenuous. We did the same for the easy route, but in this case it was the last hold.

Every time the participant touched one of the designated holds, we triggered the specific notification via the smartphone application. As soon as the participant answered, we recorded the response time by pressing a button within the smartphone app. The answer given by the participant was transcribed via a dialog within the application.

After the first climb, the participant directly climbed the second route, which was, depending on the first route either the easy or hard ascent. When the participants finished the second route, we asked them to fill out a user experience questionnaire, asking how they perceived the notification for this specific channel. This procedure was repeated two more times, testing the two remaining channels while maintaining the order of the routes. A final questionnaire was handed to the participants which assessed the overall experience and how hard they perceived the individual routes. All trials were video recorded.

In summary, the experimental design was: 12 participants $\times$ 3 conditions $\times$ 6 trials $=$ 216 data points. Overall, the study took roughly 30 minutes and the participants were compensated for their time with 10 Euros.

5.5.2 *Results*

In this section we report the collected quantitative and qualitative data. We begin with the reporting of response times, while focusing on the notification channel, the route difficulty, and the individual cues. This is followed by the participants' feedback, assessed with the user experience questionnaires and the behavior of the participants that could be observed during the experiments.

5.5.2.1 *Response Times*

To evaluate the response times, we first averaged the response times for the easy route, the hard route, and then both routes for all channels (see Figure 5.8). As it can be observed, the *light* channel has a slightly higher mean response time than *vibration* and *sound*. A test of normal distribution followed by a pairwise T-test showed no significant difference of the means between the categories. However, the standard deviation of the *light* (1323.61) channel is notably higher for both *vibration* (575.82) and *sound* (600.37).

We triggered three notifications at three distinct holds for each of the two routes to ensure comparability. Since each hold or position within the route incorporates a different difficulty of the climbing move, we investigated the response times for each position (cue) within a channel and for both routes. As shown in Figure 5.6 (easy route) and Figure 5.7

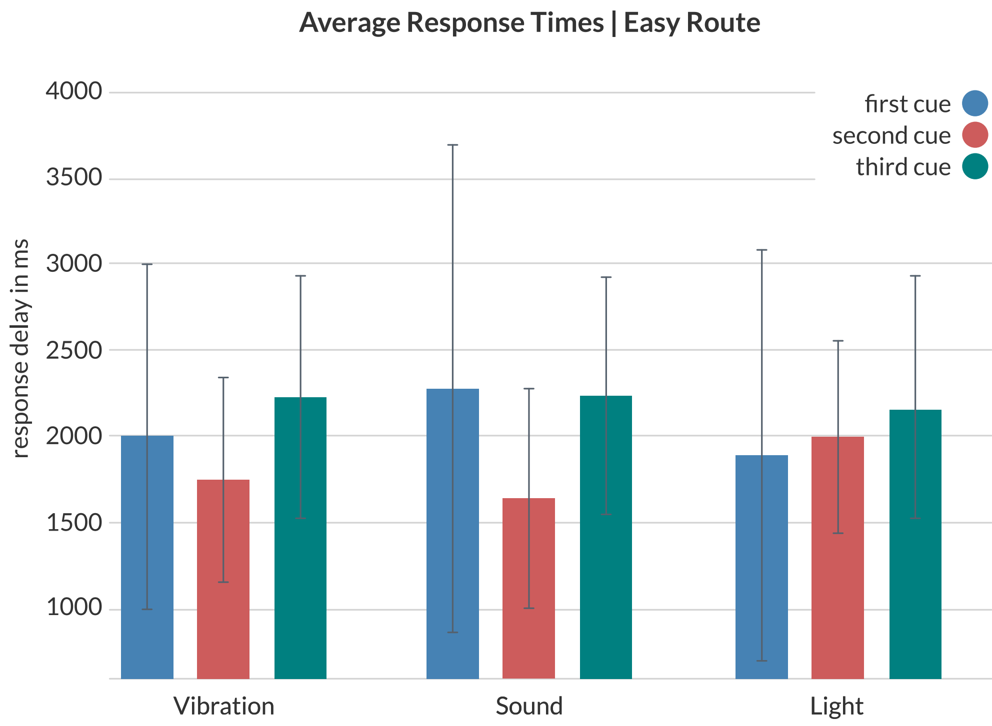

Figure 5.6: Response times for the easy route.
Response times ordered by the time of occurrence and grouped by notification channel for the easy route.

(hard route), the response times differ for each position. In the case of the easy route, the second cue for vibration and sound have a slightly lower response time than the light channel.

5.5.2.2 *Quality of Responses and Missed Notifications*

For each notification, the participant had to verbally report the level of the notification by either the number from *one* to *three*, for vibration and sound, or one of the colors *green, yellow,* or *red*, for the visual notifications. Of a total of 216 notifications, 14 notifications were missed and 4 answers where given incorrectly. We could observe that three of the 14 missed notifications were missed in the *vibro-tactile* channel while the remaining eleven notifications were missed in the *light* condition. Four notifications were missed in the easy route and ten notifications were missed in the hard route. The four notifications that were given incorrectly occurred solely in the hard route while two of them occurred during the visual and two in the vibro-tactile channel. No notifications were either missed or incorrect in the sound condition.

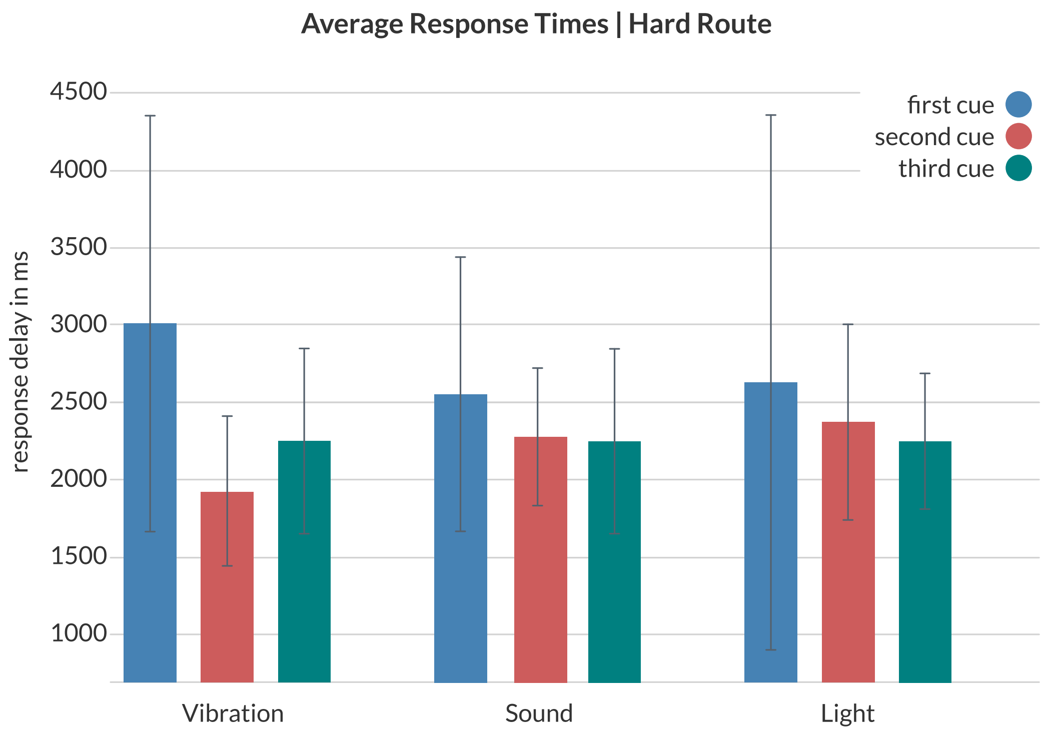

Figure 5.7: Response times for the hard route.
Response times ordered by the time of occurrence and grouped by notification channel for the hard route.

5.5.2.3 *Participant Feedback*

After each channel, we asked the participants to fill out a short user experience questionnaire. We wanted to know how the participants felt about the different channels. For this, we asked them how easy they could perceive the notification itself and the different corresponding levels. Furthermore, we asked how comfortable they conceived the notification and how they judged the efficiency of the specific channel. As a final question, the participants were asked how they liked the channel in general.

The participants stated for both, the easy and the hard route, that visual notifications are less easy to perceive than audio notifications and audio notifications are less easily perceived than tactile notifications (see Figure 5.9).

We asked the participants how efficiently they judged the perceived notification on a five-point scale, ranging from *(1) very inefficient* to *(5) very efficient* (see Figure 5.10). The light channel was judged as the least efficient with an average of 3.67 (*SD=1.24*), followed by sound with an average of 4.64 (*SD=1.14*). Vibration was rated as most efficient with an average of 4.92 (*SD=0.99*).

When asking how comfortable the participants perceived the notification on a five-point scale with *(1) very uncomfortable* and *(5) very comfortable*, sound was perceived as the

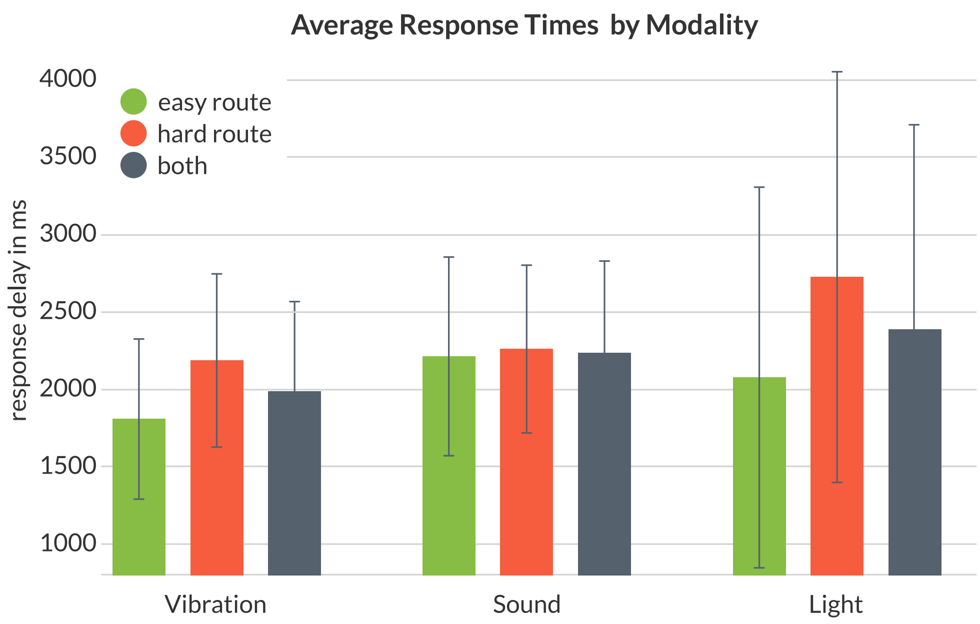

Figure 5.8: Response times ordered by notification channel and climbed route.
Response times of the participants, ordered by notification channel and climbed route.

most comfortable (*avg=4.0, (SD=0.73)*), followed by vibration (*avg=3.92 (SD=1.26)*), and light (*avg=3.27 (SD=0.98)*).

In a final questionnaire, we asked the participants how hard or easy they perceived both the hard route and the easy route (see Figure 5.9). While all the participants perceived the easy route as either *very easy* or *easy*, seven participants perceived the hard route as *hard*, one as *easy* and four participants perceived it as *neither easy nor hard*. As the last task, we asked the participants to order the channels ascending by their priority. When scoring the channels with *three* for the first place, *two* for the second, and *one* for the last place, we could observe the following order:

- vibration (29)
- sound (26)
- light (11)

This feedback is also reflected by the comments the participants gave during and after the study. Most of the participants (10) stated that the visual notification was the most distracting. They stated that this was due to the fact that when climbing during the light channel test, they felt the urge to always keep an eye on their wrist. One participant stated that he even chose his next hand hold so that he could keep the device in sight. Another participant stated that he felt forced to look at the device constantly which hindered him in focusing on the climbing itself. The fact that he missed some of the visual notifications was

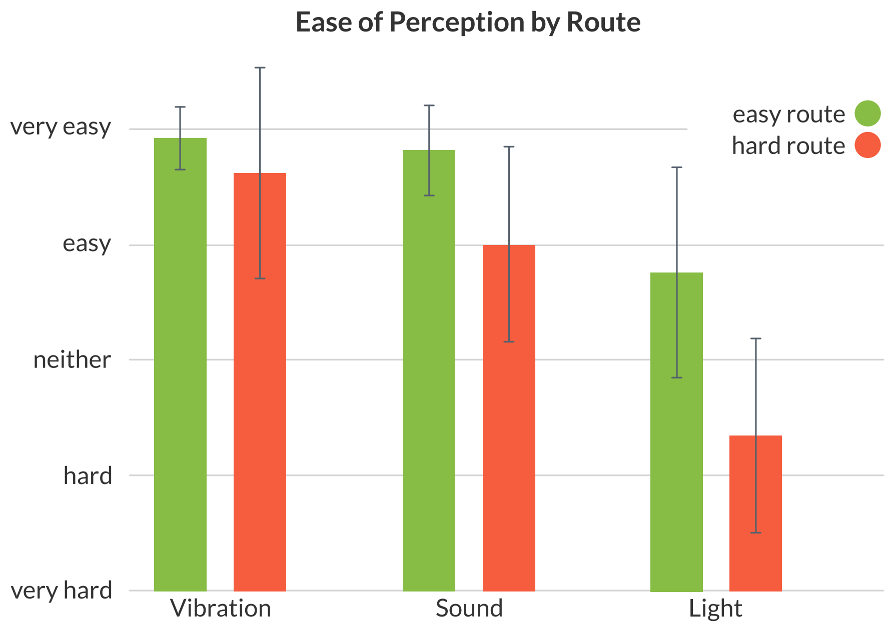

Figure 5.9: Ease of perception for the three channels, for both, the easy and the hard route.

explained by the features of the selected routes. He reported that due to the slant of the route he needed to keep his feet in sight so that he could place them on small foot holds. This lead to not having the device in sight. Two participants stated that audible notification were more easily perceived. They claimed that one is more receptive for audible cues than tactile or visual ones.

After the final questionnaire, we asked the participants if they could remember the positions where they received the notifications which were always the same for each route and notification channel. Most of the participants stated that they could not recall all the positions, but only the ones where they had the most struggle in climbing. Some participants claimed that they did not even notice that there were always three notifications and that these were always triggered at the same positions.

5.5.3 *Observed Behavior*

In addition to the subjective feedback, we also observed the participants during the experiments and did a video analysis post hoc. When testing the light channel, we noticed that some participants stopped during the climb to check if the wristband lit up during a move. Additionally, there was a large difference in response times for the light channel since some participants responded very quickly, while other participants reacted notably slower (see Figure 5.8). For all channels, we could observe that most of the participants responded *after* they completed their move to the next hold and very seldomly during a

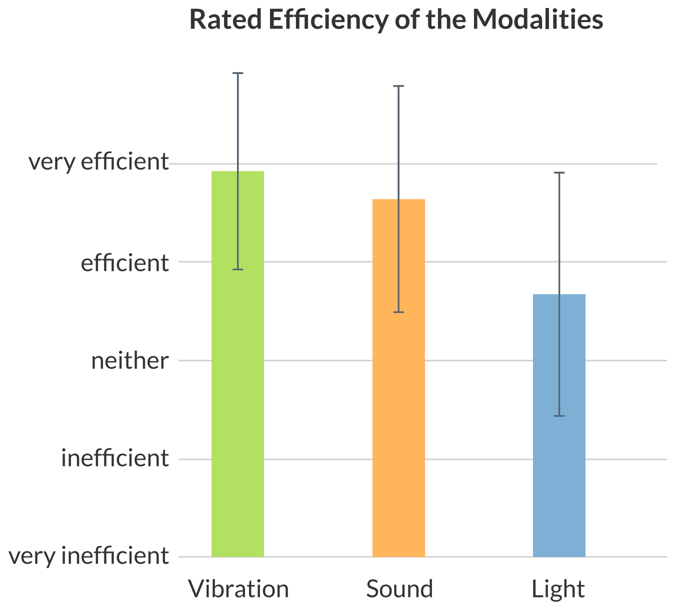

Figure 5.10: Answers to *How efficient do you think this notification is?*
Answers to the question *How efficient do you think this notification is?*

move, also attributing for the standard deviations. Another observation that surprised us happened during a participant's ascent of the hard route while testing the light channel. We witnessed that he had the wristband in sight during the notifications, but he was so focused that he did not perceive one of the three notifications. After climbing, we asked him if he actually perceived the notification but forgot to report it, but he claimed that he, in fact, did not perceive the visual notification at all.

5.6 DISCUSSION

The results of both studies lead to promising results that can inform the future design of climbing technology. After discussing the results, we explore potential application areas to support climbing and address the validity of the perception study.

5.6.1 *Perceptual Differences of Routes*

We analyzed the individual moves at which we triggered the notifications in the video footage. Figure 5.7 shows the average response for each move with the corresponding channels. The hard route was physically demanding right from the start, after which the first notification was directly triggered. The level of exhaustion and cognitive load also becomes evident in the average response times throughout all modalities. Compared to the

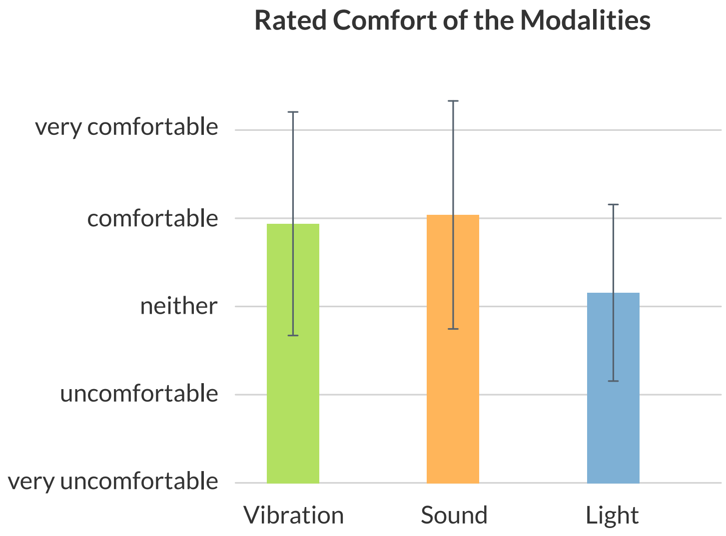

Figure 5.11: Answers to *How comfortable did you perceive this notification?*
Answers to the question *How comfortable did you perceive this notification?*

other holds where notifications were triggered, the response times of the first hold on the hard route were considerably larger. One explanation for the higher standard deviation in the first as well as in the last move is that some climbers experienced this specific move as easy, for example, due to their reach, and others struggled at this specific part. During the ascent of the last route, some of the climbers were visibly exhausted, which accounts for the higher standard deviation but similar response time. This explanation is in line with the video recording of the individual climbs. No climber struggled at the middle part of the route which lead to a small standard deviation and smaller response times compared to the starting move in all channels. The individual moves of the easy route can be explained analogously and also stay in accordance to the observation we made in the video (see Figure 5.6). It is possible that a low standard deviation and low response time are an indication for a move that was perceived as easy by all climbers and vice versa. When comparing the average response times of the easy and hard route, we noted that the climbers response time was notably slower for the hard route in the vibration and light channel whereas there was only a negligible difference for the sound channel. The error rates and the number of missed notifications in the hard route imply that notifications are more difficult to perceive towards the upper limit of the climber's difficulty spectrum (see Figure 5.8).

5.6.2 *Visual Notifations*

Although, in a variety of sports, watches with graphical displays are well established, visual output does not seem to be suited for real-time feedback in climbing, as we observed several disadvantages that do not outweigh its advantages. The wristband prototype created simple visual cues, which did not require the participant to read text or interpret graphics. However, the visual output of a plain green, yellow, or red light can be understood as a very simple form of a display. Despite its visual simplicity, the majority of the participants (10 out of 12) stated that they felt the urge to always keep the device in sight, which could explain the similarity in response time to the other notification channels since they were explicitly informed before each climb that they will receive visual cues. The same group of participants also reported a decrease of their climbing performance as they felt distracted by the need to constantly watch their wrist, even in periods when there were no notification. These observations stay in accordance with objective measures we gathered: light was the slowest channel with an average response time that was 1.2 times higher compared to sound and vibration during the hard climb (see Figure 5.8). In the easy as well as in the hard climb, the average response times and the standard deviation of the *light* channel are notably higher for both *vibration* and *sound*. Although there was no significant difference, we still think that this is an important finding, which is strongly reinforced by the subjective user feedback. The high standard deviation can be explained by personal strategies of the participants that were revealed by the subjective comments and observations. They either periodically stopped their primary task (climbing) and checked the device or only occasionally glanced at it.

Furthermore, $78,57\%$ (11 out of 14) of notifications were completely missed during the visual condition. It was also subject to the highest standard deviation in terms of response time, which indicates that some climbers reported notifications exceptionally slow, while others responded normally. If we regard the per move analysis in Figure 5.6 and 5.7, the light channel can be identified as a clear outlier, while the participants responded similarly to vibration and sound notifications.

5.6.3 *Tactile and Audible Notifications*

When looking at the ease of perception in Figure 5.9, it can be observed that both vibration and sound outperform the light channel. This also applies to the subjectively assessed efficiency and level of comfort of the channels. Both channels, vibration and sound, were ranked between very high and high for all three categories (*ease of perception, comfortability*, and *efficiency*). This is also reflected in the evaluation of the final questionnaire where both channels are close to each other on the first (vibration) and second (sound) rank. However, the audio channel outperformed the vibration channel in terms of the average the response time. This is due to the fact that this is the only channel in which only a negligible performance difference could be observed in terms of response time between the hard and the easy route. Moreover, the participants subjectively rated sound as being the most comfortable of all channels (see Figure 5.11). For climbing outdoors, the pair of wireless bone conducting headphones could also be integrated into a climbing helmet. We did not consider Google Glass as an output methodology as something attached to the forehead could lead to severe injuries in case of a fall. Even though we found the light channel to be less suited when attached to the wrist, it might still be useful when it is located on the top part of a helmet where it could act as a cue in the peripheral view.

5.6.4 *Limitations*

Although the results of the perception study provide insights into indoor climbing, we cannot be certain that the same findings apply to outdoor climbing in more extreme environments. Placing self-set protection in cracks of rocks introduces additional psychological and physiological challenges, which may lead to even longer response times than those observed between the easy and hard routes in the study. Furthermore, we would like to highlight the difficulty of finding and designing routes that are equally challenging for a specific group of climbers. Every climber perceives the difficulty of the same route differently due to variations in body height, arm length, body weight, flexibility, and other physical characteristics. In this regard, having a homogenous group of participants with identical body characteristics might have yielded more definitive results in the perception study.

5.6.5 *Application Scenarios*

Real time on-body notifications in climbing could be used in a variety of situations and systems. We identified two main areas: (1) skill assessment and technique monitoring and (2) climbing assistance. The successful ascent of a route depends on both of these areas. A good climbing technique plays an important role in sports climbing. Examples for that are the efficient use of grip power, the placement of the climber's body's center of mass below the arms, and to keep the elbows unbent whenever possible to save power. Another important factor is an efficient flow of movements. It is good practice to leave hard parts of a route behind as fast as possible to find a more suitable position to rest the arms. This is only possible if the climbers know which hold to use next such as if a placement of a foot could make them reach a hold which is seemingly far above them or twist themselves in a position which optimizes their center of mass.

An experienced climber or trainer can be of great help to assist the climber, but only if both are in immediate hearing distance. A notification system as described and tested above could either facilitate the communication with both parties, or in case of an autonomous climbing assistance system, be used as an output medium. We believe that each channel has its advantages and disadvantages for communicating different information. The results mentioned above suggest that visual notifications are not ideal for time-critical and immediate notifications. In contrast, a gauge that communicates to the climber how much power they have left would be an example of a good use of visual notifications. The climbers could glance on the device occasionally to decide whether they should take a break to ensure that theirs muscles will not harden, so that they can continue to climb later in their climbing session. As opposed to the visual notifications, vibro-tactile or audible notifications could be used in an autonomous system to give the climber an immediate hint to stretch the arms again if the system detects a lasting contraction of the biceps.

5.7 CONCLUSION

In a preliminary online study, we determined the most appropriate body parts for wearables to trigger notifications during climbing. In general, the wrist was found to be the most appropriate body part at which we triggered light and vibro-tactile notifications. The sound channel was implemented with a pair of wireless bone conducting headphones, following the results of the online study. We further investigated the abilities of a climber to perceive vibro-tactile, audible, and visual cues under the condition of climbing both, a relatively easy and a hard route. Each channel could transport the information of three different levels. We assessed response times, error rates, and climbing duration as objective measures of the climbing performance, as well as subjective measures with questionnaires that were filed after completing a notification channel. The perceptional study revealed that both audible and vibro-tactile feedback are suited for real-time notifications during climbing. Overall, sound was rated slightly better than vibration. In accordance with related work, our results indicate that light is inappropriate as a real-time notification channel during climbing, especially in challenging routes. This was shown by slowest response times, highest error rates, and the most missed notifications-

In the future, the investigation of members of a competitive climbing team could lead to new insights. Training in a professional climbing team is very rigorous. This allows the study of the perception in different states of exhaustion and on a broad variety of difficulties in highly-controlled experimental conditions. Furthermore, varying levels of notifications could be tested or even secondary tasks like solving a math problem. Finally, testing the output modalities in actual applications that include meaningful applications in a climbing context as laid out in the scenarios above would reveal the real-world applicability of the notifications tested.

5.8 CONTRIBUTIONS TO THE RESEARCH QUESTIONS

This work contributes to **RQ 1** and **RQ 3**.

What are factors influencing the acceptance and willingness of athletes to use a computer-supported assistive system for sports training?

RESEARCH QUESTION 1 Depending on how an assistive system is implemented technology based sensing and feedback needs to be integrated either in the environment, in wearables, or in a combination of both. In this work, we conducted an online study with 54 climbers to explore acceptable body positions for wearable devices. The results showed that the wrist was perceived as the most appropriate position for wearables, while the foot was rated as the least suitable. Interestingly, even positions that might initially seem impractical, such as near joints or other restrictive areas, could be tolerated if the perceived benefit of the device was strong enough. However, the natural assumption that wearable devices must not hinder athletes in performing their sport was generally confirmed. This includes avoiding placements that interfere with flexibility or movement, such as joints, which climbers explicitly identified as problematic areas. These insights underline the importance of involving the target audience early in the design process to ensure the system aligns with their needs and expectations.

How could computer-supported assistive systems communicate feedback and instructions to athletes during training?

RESEARCH QUESTION 3 This work investigated output modalities for low density information content during rock climbing. The perception study with 12 climbers demonstrated that sound and vibration are the most effective notification channels during the physically and cognitively demanding ascent. Visual feedback was found to be inappropriate, as it required climbers to constantly monitor the device, distracting them from the activity. This was especially true for demanding routes. Feedback modalities should be designed with the context and time requirements in mind. While visual notifications were not appropriate for real-time applications, they could, however, still be suitable for ambient notifications, such as indicating the time spent on the route or the climber's distance to the next bolt in an outdoor setting. Audible and tactile notifications on the other hand proved to be easily perceivable, more or less regardless of the difficulty of the route. The findings are particularly relevant for scenarios where the user's visual focus and hands are heavily engaged, as in rock climbing or downhill skiing.

6

VISUALIZATION APPROACHES FOR REAL-TIME EXPERT MODELLING IN ROCK CLIMBING

In the previous chapter we proposed and studied different real-time feedback methods to provide notifications with a low information content. We envisioned the use of this information to automatically notify the climber in case of muscle fatigue or to provide an ambient display informing about the distance to the next belay station in an outdoor scenario. However, to provide feedback with a higher information content, these feedback methods are only of limited use. In this chapter we propose different visual feedback method to be used by climbers to learn a specific climbing technique. With this, this chapter contributes to **RQ 1** and **RQ 2**. The contents of this chapter have been previously published in the following publication.

Felix Kosmalla, Florian Daiber, Frederik Wiehr and Antonio Krüger. "Climbvis: Investigating in-situ visualizations for understanding climbing movements by demonstration". *In: Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces.* ISS'17, USA [130]

6.1 INTRODUCTION

As already mentioned in Section 3.3.1.1 climbing is a complex activity that is determined by a variety of physiological and anthropometric factors. Although rock climbing, especially indoor rock climbing, is a trending sport, learning basic climbing techniques is still a challenging task for beginners. Typically, bouldering gyms consist of artificial blocks or walls of various shapes on which climbing holds are mounted. The objective of the climber is to ascend the walls while using only a predefined set of holds (a *route* or *problem*) to grab and step on. Often these routes require the climber to use a certain set of climbing techniques to not only reach the top but also do this in a graceful and energy-efficient way. The classic approach to understanding these techniques is applying them on a specific problem. Usually this is done in pairs of the trainee and a more experienced climber (trainer) demonstrating the route. As opposed to other sports which involve complex movements like martial arts or ballet, the trainee cannot mimic the instructor in parallel, since the instructor is using the climbing wall (i.e. the specific route) while demonstrating. Except for so-called speed climbing walls, it is very uncommon to have the same setup of holds next to each other which would allow such a mimicking. This bears the disadvantage that the

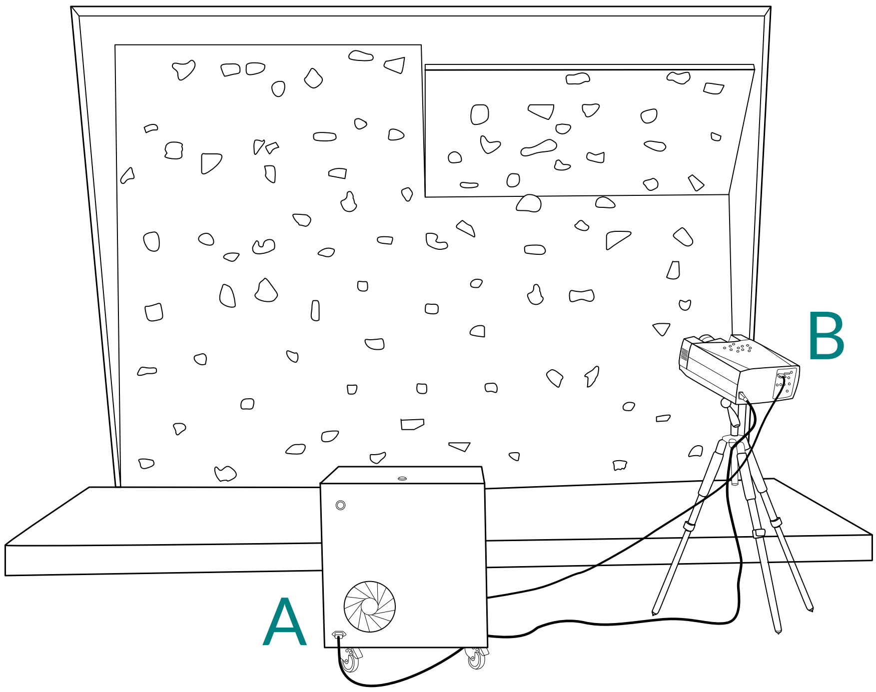

Figure 6.1: The setup of the experiment: (A) the betaCube [237] camera projection unit consisting of a projector and a Kinect V2 camera, and (B) a second projector for local, high DPI projections. Projector B could be omitted when using a 4K projector.

trainees have to remember every nuance of the movements, including how to shift their body weight, how to grab a certain hold, where to hook their feet, and the dynamics of a move, i.e. how to use the inertia that is building up throughout the ascent. To overcome this issue, we propose a system for visualizing climbing movements in an indoor climbing gym. The system allows the trainees to see themselves in parallel to the trainer's movements. This is accomplished by using a movable camera projection unit, as described in [237], filming both the trainee and instructor from behind during a climb. The resulting augmented real-time video footage can be presented to the trainee via different visualization methods: a Google Glass, a projected display, or a life-size in-place projection of the instructor on the climbing wall. We envision the use of the system as described in the scenario below.

Scenario
Sarah and Paul meet up in a local climbing gym. Paul has just started climbing while Sarah is an experienced climber willing to show Paul some moves. They find an interesting climbing problem that Paul has some trouble with. To help explain the problem to Paul, they roll the camera projection unit in front of the bouldering wall and start the calibration process by pressing a button. A smartphone app remotely connects to the unit and controls the video recording function.
Paul starts the recording and Sarah demonstrates the ascent of the route. Now Paul can pick a visualization method which suits him and the problem the best. By following the movements of Sarah in the recording, Paul can more easily ascend the route.

All three methods were evaluated during a lab study with 12 participants who either have never climbed before or are early beginners who have not engaged in climbing technique training before. The results of the study showed that the life-size projection was the easiest to follow while most of the participants had problems switching context between the augmented third-person video and the climbing wall. In this paper, we provide three main contributions. First, we propose a flexible system which uses a Kinect, projectors, and a Google Glass[1] for instant climbing movement visualization for interactive climbing spaces. Second, we introduce three visualization methods for understanding climbing movements by demonstration. Finally, as a third contribution, we identified a number of issues that are critical for the design of in-situ video feedback methods. In order to address these issues, we suggest an in-situ hybrid video feedback approach.

6.2 BACKGROUND AND CONTEXT

Climbing is a sport that is determined by a variety of physiological and anthropometric factors. Lopera et al. [145] investigated the effect of indoor climbing on strength, endurance, and flexibility in novice climbers. Their study reveals that novice climbers quickly improve their climbing performance, but they do not significantly gain more muscular strength and endurance compared to experienced climbers. This indicates that improving climbing technique, over strength and stamina training, should be focused on when introducing climbing to beginners. In this work, we explore ways to assist novice climbers in this respect.

6.2.1 *Video Feedback and Expert Modeling*

In sports psychology and motor learning research, some work exists that investigates video feedback (e.g. soccer coaching [88, 89]) as well as expert modeling as training tools. In video feedback, positive as well as corrective feedback is given to the athletes based on

1 https://www.google.com/glass

video recordings of their own performance. Conflicting studies on the efficiency of video feedback in sports training have been published: Studies on video feedback in golf [90] and tennis [230] found no significant differences compared to traditional feedback methods, while others presented promising findings that may inform the design of future video feedback systems (e.g. for soccer [88, 89] and ice hockey amateur coaching [184]).

In contrast to analyzing videos of own performances, expert modeling uses videos of an elite athlete that present the correct execution of a specific skill and show the performance to the trainee. Some approaches aim to improve complex athletic performance by combining expert modeling with video feedback (e.g. [24, 188]). This approach enables the athletes to compare video recordings of their own performance with videos of an elite athlete correctly executing the movement. In this work, we go beyond existing video feedback and expert modeling techniques by applying an approach that provides in-situ feedback during rock climbing.

6.2.2 *Augmented Movement Guidance*

Performing the correct movement in sports is important to achieve a certain goal. When it comes to rehabilitation exercises or physiotherapy, it is even more crucial that the movement is executed correctly. There has been some research in the human-computer interaction (HCI) community that addresses this problem, as presented in Section 3.2.4.

In *physio@home* [218], the authors developed a system for guided physiotherapy at home. For this, they used a high precision tracking system to track the user's limbs. A screen in front of them guided the user through different exercises while showing a mirrored live image of the user, augmented with visual guidance on how to move. In *SleeveAR* Sousa et al. [211] presented a system that gives real-time feedback for rehabilitation exercises by projecting guidance and performance feedback on the users' sleeve and the surrounding floor. Sodhi et al. [210] proposed *LightGuide*, a guidance system that projects guidance hints directly on the user's hands. In a user study, the authors could show that with their real-time guidance system, the participants could perform movements nearly 85% more accurat than when guided solely by a video recording. Similar to that, we used augmentation on both the surrounding and body of the climber to guide her during the ascent via video feedback and expert modeling. This work is inspired by research from sports psychology and motor learning and contributes to the design and evaluation of video feedback techniques in HCI and sports. In particular, the proposed approach goes beyond existing video feedback and expert modeling techniques by investigating an in-situ feedback mechanism while actually performing complex (climbing) movements.

6.3 IN-SITU VIDEO FEEDBACK

The classic approach of presenting a particular climbing technique or a solution to a climbing problem is the demonstration of the sequence of movements by a more experienced climber ("instructor"). Followed by the demonstration, the trainee tries to mimic the instructor's movements. This has the disadvantage that the trainee has to remember every nuance of the instructor's ascent. To overcome this issue, we propose two different visualization techniques on three different mediums which allow the novice to climb a route while getting in-situ video feedback and expert modeling.

Figure 6.2: A full-size video of the instructor is projected in-place on the climbing wall. The trainee has to mimic the body posture of the projection.

Scan QR-Code for Video

6.3.1 *Life-Size Shadow View*

We provide the trainee with a life-size projection (*Life-Size*) of the instructor, which is displayed in-place on the climbing wall with a very precise spatial matching from recording to projection. For this, we use the technique of the betaCube [237], a self-calibrating camera-projection unit. The unit comprises a Kinect v2, a 6000 lumen short-throw projector and a laptop. After an automatic calibration phase, it is possible to record a video and play it back at the exact same position where it was recorded, making it possible to project a detailed representation of the climber back onto the climbing wall.

Figure 6.3: During the ascent, the trainees see themselves from a third-person perspective through the Google Glass.

6.3.2 *Augmented Third-Person Views*

The trainees are provided with a video stream of themselves from a third-person perspective that is augmented by a video recording of the experienced climber while ascending the route. Due to the fact that both video streams are recorded from the same camera and point of view, an exact match of both videos is guaranteed. For this method, we chose a projected display (*Display*) (see Figure 6.4) and Google Glass (*Glass*) (see Figure 6.3) as the display. Both videos were recorded in Full HD and streamed with a delay of approximately 250 ms. The video stream was cropped so that only climber and video of the expert were visible and scaled in respect to the replay medium (640x360 pixels for Google Glass and 1024x768 pixels for the projected display).

The choice favored a projected display as opposed to a conventional flat screen display since the projected display can be placed on every position on the climbing wall without the danger of breaking or injuries. When choosing the head mounted display, we had the option of (a) [2] (b) a Recon Jet[3], or (c) Google Glass. Despite their binocular vision, we dismissed the Epson BT 200 augmented reality glasses because of their heaviness and the fact that they included a wired processing unit, which would have constrained the climber. While the Recon Jet, a monocular heads-up display including polarized lenses, has a smaller form factor, we found that the video quality with a resolution of 428x240 pixels was not sufficient

2 https://tinyurl.com/4npehj38
3 https://www.synapse.com/work/recon-jet/

to recognize details of both climbers on the wall. Our final decision went in favor of the Google Glass. The video displayed in the Google Glass was easier to see and provided the climber with a higher resolution video (640x360 pixels). Furthermore, the Google Glass is lighter than the other options. During the trainee's climb, only a submovement of the complete ascent of the instructor is displayed to the trainee, while looping continuously. As soon as the climber mimics the movements of the instructor, the next sequence is queued manually. These sequences lasted 3.1 s in average ($SD = 1.3$ s).

Figure 6.4: An augmented third-person view shows the trainee superimposed on a looping video of the trainer performing the correct movement.

6.4 STUDY

To assess the effectiveness and user experience of the proposed visual feedback methods, we ran a controlled laboratory experiment to compare the classical, in-person demonstration approach to the three in-situ visualizations of climbing techniques described above.

6.4.1 *Participants*

We recruited 12 participants (4 female, 8 male) through university mailing lists and social networks. The only requirement was that participants had neither climbed nor participated in climbing technique training before. As an incentive, we offered 10 EUR for their participation. The participants' ages ranged from 22 to 32 years ($M = 26.5$ years, $SD = 3.6$ years). Participants reported engaging in 1 to 10 workouts per week ($M = 3.5$, $SD = 2.7$), including fitness (3), triathlon split training (2), mountain biking (1), horseback riding (1), martial arts (1), and running (2). One participant wore prescription glasses throughout the experiment. Informed consent was obtained from all participants.

6.4.2 *Conditions*

In this study, we investigated four different feedback methods (see Figure 6.5).

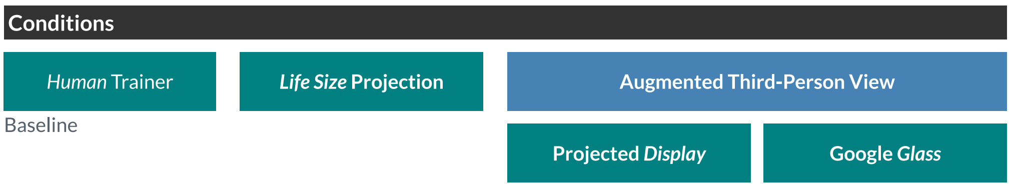

Figure 6.5: Study conditions investigated. The Human Trainer served as baseline. Life Size-Projection projected a video recording of the trainer directly onto the wall. The Augmented Third Person View showed the video of the trainer overlaid with the real-time performance of the trainee. This view was used in two conditions. Project Display displayed the view on the climbing wall, in the view field of the climber. In the Google Glass condition the view was displayed in the glasses worn by the climber.

HUMAN Following the classic approach, a human trainer demonstrated the movement for the participants.

LIFE-SIZE The movement to be learned was projected directly onto the climbing wall. This resulted in the recording of the trainer being played back exactly where it was recording. The virtual trainers hands and feet would seemingly touch climbing holds, creating an immersive visualization of the instruction (see Figure 6.2).

GLASS An augmented third-person view of the trainee was superimposed over the looping recording of the trainer performing the movement (see Figure 6.3).

DISPLAY The same visualization was presented as projected screen in the view field of the climber on the climbing wall (see Figure 6.4). Here, the position of the projected display was fixed and chosen so that the participant had a clear view on the projection as visualized by a red rectangle seen in Figures 6.6, 6.7, 6.8, and 6.9.

6.4.3 *Apparatus*

The study was conducted around a small climbing wall (4m in width, 3m in height) in our lab. Due to the short height of the climbing wall, a thick mat sufficed as protection in case of possible falls. The setup as shown in Figure 6.1 consisted of a camera projection unit and

(B) a second projector mounted on a tripod. We used the Kinect v2 camera to record both the videos from both, the trainer and trainee resulting in videos obtained from the same perspective. To play back the life-size videos, the recording was spatially mapped to the climbing wall as described in [237], based on a camera-projector calibration obtained via the RoomAlive Toolkit [110].

Usually in a climbing gym, colored holds are mounted on artificial climbing walls. Holds of the same color define a route and only the holds of one route are allowed to be touched or stepped on. In our study setup, only black and gray holds were mounted on the climbing wall. We used the camera projection unit to highlight individual climbing holds to guide the participant during the experiment.

The second projetor (B) was used to display a higher resolution image at specific locations on the climbing wall. This was used for the *Display* condition.

6.4.4 *Tasks*

During the experiment, the participants were asked to climb four routes. Each route entailed a specific climbing technique which was demonstrated to the participants. All climbing techniques were selected so that they are not overly complex but challenging enough for a novice to make room for improvements.

FLAGGING Flagging is a static method to keep the climber near to the wall when using hands and feet on only one side (e.g. only the left or right side). When moving upward from this position, the opposite leg (in this case the right one) swings around the center of the body (a.k.a. barn door), leading to an unbalanced body position. To overcome this, the right leg is put in front of the left leg, pointing away from the body. This prevents the swinging of the whole body to the right (see Figure 6.6).

OUTSIDE EDGE Outside Edge is a power saving technique. While ascending, the goal is to rotate the hips so that the side of the body is parallel to the wall. This very stable position allows the climber to step up with her free leg (see Figure 6.7).

THE ROCKOVER The Rockover is a technique for slabs or easy-angled routes. The climber is shifting her body over so it is directly above the hold that she is stepping onto. The movement goes to the side and not upwards (see Figure 6.8). Once rocked over, the climber can then use leg strength to push up into a standing position.

TWISTLOCK The twistlock is usually used when trying to grab a hold on an overhanging part of the climbing wall. By rotating around the climber's body axis and simultaneously locking the grabbing arm, she can reach a high hold more easily (see Figure 6.9).

Figure 6.6: Flagging is a climbing technique that helps the climber to keep her balance when only having holds for one side of the body. The red rectangle depicts the fixed position of the projected display.

6.4.5 *Procedure*

After a brief introduction to the experiment, the participant was asked to sign an informed consent form, whereupon video and audio recording was started. Before beginning with the actual experiment, the participants were asked for their demographic data, whether they were wearing glasses, and what and how many sporting activities they do per week. Followed by that, four routes were climbed by the participant, each using a different visualization. To become familiar with each visualization/instruction method, we introduced a practice which participants had to undergo before climbing with the respective visualization.

TRAINING TASK Before climbing, each participant was given an introduction to the visualization used for the upcoming route. Following this, the participant completed a trial, non-climbing movement while standing on the floor with the current visualization by copying a sequence of movements displayed to them. The sequence began with the instructor standing on the ground and gripping two holds to his left and right. The instructor then touched a different hold with his left hand, returned it to the initial hold, and repeated the same steps with his right hand, followed by both feet, one at a time. In the *Human*

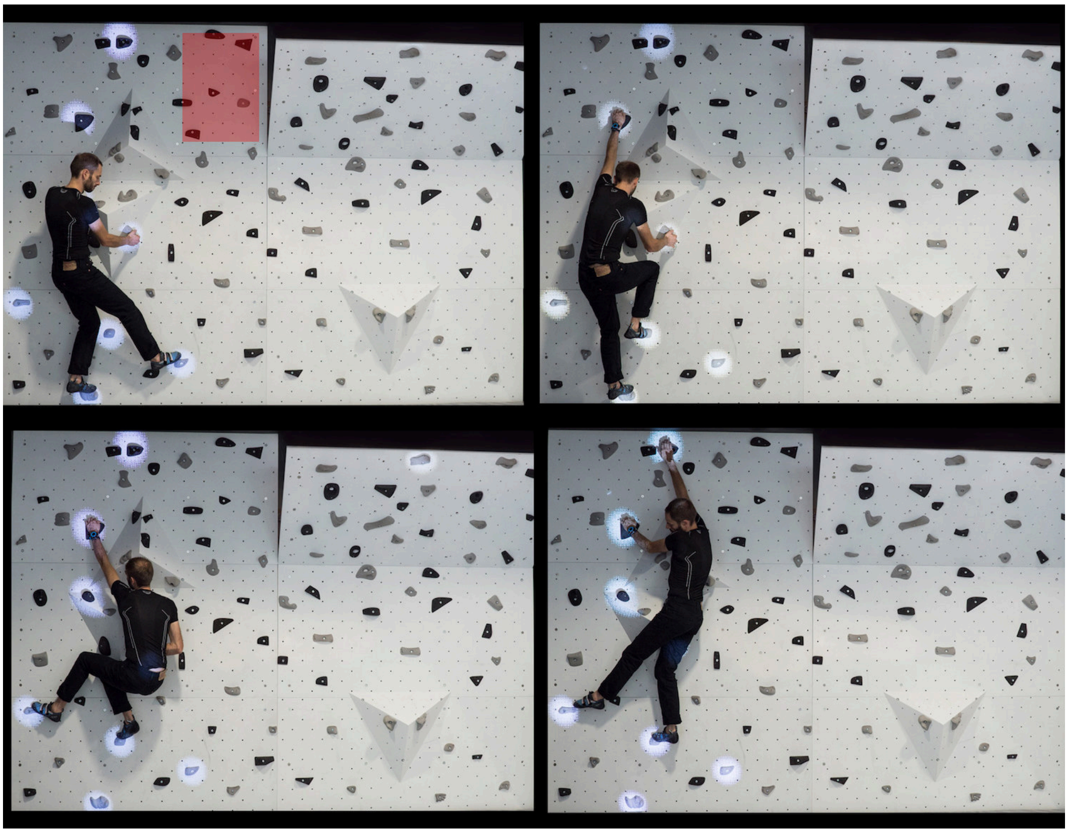

Figure 6.7: Outside Edge. The climber rotates the hips so that the hip opposite the pulling hand is turned into the wall. The red rectangle depicts the fixed position of the projected display.

condition, the experimenter demonstrated the sequence in person. Participants were asked to position themselves in the same spot as the instructor and replicate each move. When the participant correctly touched the designated hold, the experimenter advanced to the next movement by pressing a button on a remote control.

After completing the training task as described above, the participants were asked to climb the route three times:

1. In the first attempt, the participants were instructed to climb the route in any way they saw fit. The only requirement was to use only the highlighted holds.
2. In the second attempt, the participants were asked to copy the climbers' technique as closely as possible. Depending on the condition, they were shown one of the visualizations, one step at a time. As soon as the participants progressed in the ascent, the visualization displayed the subsequent step.
3. In the final attempt, the participants were asked to repeat the technique without any augmented feedback, if possible.

Figure 6.8: Rockover is a climbing technique in which the climber rocks onto a hold by moving sideways instead of upwards. The red rectangle depicts the fixed position of the projected display.

This procedure was conducted for each of the four visualization methods on the four different routes. While the order of the visualizations was alternated in a latin-square, the order of the routes stayed the same. This resulted in a total of 4x3 trials per participant. The climbing session was followed by a semi structured interview. Overall, the study took around 45 min. per participant. We compensated the participants with 10 EUR each.

6.4.5.1 *Semi-Structured Interviews*

After the participants completed the trials, we conducted semi-structured interviews with them. The questions mainly concerned the different visualization techniques:

- How easy or hard did you perceive the matching from *Display* or *Glass* to the climbing wall?
- Could you imagine using one the visualizations in a climbing gym and if so, do you think that you could learn to climb better with one of them?
- Could you imagine that one of the visualizations could be an alternative to a human coach?

Figure 6.9: Twistlock. By rotating around the climber's body axis and simultaneously locking the grabbing arm, she can reach a high hold more easily. The red rectangle depicts the fixed position of the projected display.

- Where do you see the advantages and disadvantages of the live feedback as opposed to demonstration via a human coach?
- *Final Conclusion*: Please rank the visualizations from best to worst and explain why.

6.5 RESULTS

6.5.1 *Human Feedback vs. Augmented Video Feedback*

The participants were asked to compare the classic approach using human feedback to augmented video feedback in general, regardless of the used visualization.

In general, human feedback was acknowledged for its in-person communication possibilities *"You have someone who can give you tips in person and whom you can check back with"* (P7); *"With auditive instructions, I can focus on the climbing and do not have to look at other parts of the wall"* (P8). However, mimicking the demonstration was criticized since it requires the novice to recall the whole climbing sequence: *"The expert can explain it to you,* *but you cannot directly repeat it without remembering what to do"* (P3); *"I need to remember the things and cannot do the movements at the same time as the instructor. With harder routes, that is probably challenging"* (P7); *"When [the instructor] did it, it is much better but only in small demonstrations. With very long routes, I would definitely forget what [he] did. So I could remember one or two steps. Otherwise, I would have to look at the Google Glass or whatever was helping me"* (P5). P1 doubts that human feedback during the climb is effective: *"During the climb, the trainer can't give enough feedback. The trainee has to do a matching from speech to action"*.

Video feedback was positively valued for its in-situ, in-place, visual guidance: *"I see what needs to be done, so I don't have to understand what the trainer is saying"* (P1); *"Seeing yourself is very helpful. It's the same thing when doing ballet in front of a mirror"* (P2); *"The video feedback is better because I understood faster what to do"* (P7); and for its independence from the availability of an instructor: *"You do not need an expert at hand"* (P3); *"I could do this whenever I wanted without an expert by hand"* (P4); *"You don't depend on an expert"* (P8). Social aspects also play a role *"Maybe some people would feel more comfortable with video feedback because they don't want to embarrass themselves in front of a trainer"* (P10); *"I can climb it my own pace and don't feel stressed because I am being watched"* (P12). A drawback of the video feedback was that some participants mentioned problems in correctly perceiving the demonstration of the expert: *"I need to understand the visualization. I see the visualization, I think to know what I need to do, but this might be totally wrong"* (P2); *"I think the video feedback is not suited for real novices but beginners who already have a rough understanding of how to move on the wall"* (P6). Another problem with the video feedback techniques was the quality of the visualization: *"Body rotations were hard to recognize because of missing contrast"* (P2); *"Missing depth perception"* (P4).

6.5.2 *Video feedback*

The participants were asked to comment on the individual video feedback techniques and the alignment between the video and the real world.

6.5.2.1 *Video Feedback Techniques*

The participants were asked to vote for their favorite video feedback technique and justify their choice. Life-size was voted highest, directly followed by the Display condition, while Glass and Human condition placed a distant third (see Figure 6.10).

LIFE-SIZE PROJECTION The *Life-Size* video feedback was appreciated because it was easy to understand and follow: *"Very easy to understand and copy."* (P4); *"Very good, it would be even better with back-projection"* (P5). On the other hand, the occlusion of the projection was seen as a problem by P2, P5, and P6.

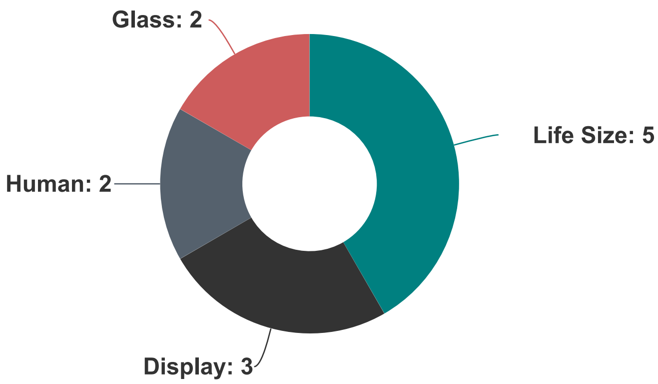

Figure 6.10: Votes for the individual visualizations. A vote for a specific visualization was counted when named as favorite technique by the participants.

PROJECTED DISPLAY The *Display* condition was favored because of its constant position and unambiguity: *"I could recognize everything, and it was unambiguous"* (P6); *"You can fit yourself in the image, and it's alway there at the same spot"* (P4). However, P5 did not like that he had to look at different part of the wall to see the visualization.

GOOGLE GLASS P2 found that the use of the Glass display had the advantage of being inconspicuous, as opposed to projection, which could be seen by other climbers in his surroundings. P5 commended the fact that for the Glass he did not have to look around him but rather just switch focus onto the display of the Google Glass. However, P1 and P7 complained about the image quality and size of the video *"Display too small"* (P1); *"Too small, I could not recognize the holds"* (P7).

6.5.2.2 *Visual Alignment*

Another dimension of the semi-structured interview addressed the alignment of video content and real-world objects, i.e. which is the next hold the participants should put their hand or foot on, or in which direction to shift their center of mass.

LIFE-SIZE PROJECTION In the Life-Size video feedback, the matching was perceived very well and unambiguously: *"The matching was very easy"* (P2); *"The Life-Size projection was the easiest because it's the same thing"* (P4); *"Matching was very fast and easy"* (P8); *"With the life-size projection, the danger of confusion was much lower"* (P9); *"The Life-Size projection was easier to understand"* (P11). Occlusion was identified as a common issue *"Some minor issues arose when occluding the projection with my body"* P2, *"It was hard to see holds that are close by"* P5, *"For the projection it was unambiguous, but sometimes it was hard to keep track of every movement that was displayed"* P6, while P3 describes occlusion as a feature *"I occluded the projection sometimes, but then I felt safe because I knew that I am in accordance with the expert"*.

PROJECTED DISPLAY Display was also rated very well with respect to matching and the most preferred technique by some participants, because the expert modeling was well perceivable *"The Display was the most comfortable since you could always see yourself in reference to the expert"* P6 and the display was located at a fixed position which allowed for easy focus switches *"Display was better than Google Glass because the image was larger and more in my field of view"* P8. One participant had problems with the matching in third-person view *"It was unfamiliar when seeing myself from behind. You have to orient yourself in the video image, and then you have to transfer that back to the wall to recognize which hold to grab"* P11.

GOOGLE GLASS In addition to the aforementioned problems with the Glass, it was also criticized regarding alignment. Besides the general problem with image quality and size (P1: *"Extremely hard because the image was too small"* P6: *"I couldn't recognize details in the video"* P12: "It was hard because the image was blurry"), the main issue here was the context switches between wall and Glass *"Hard because I could not focus on the display of the Google Glass while looking in the direction of the wall"* (P2); *"Google Glass was the most challenging. Because I had to look at the Glass first, then at the wall, and then back to the Glass to verify my movements"* (P8); *"I had problems getting the focus right"* (P9); *"It was hard to concentrate on both the Google Glass and the climbing. Another problem was focusing."* P10.

6.5.3 *Analysis of Video Recordings*

In addition to the semi-structured interviews, we (two experienced climbers) visually analyzed the video recordings. We examined both the first and the third ascent of the participant. Both ascents were executed without any assistance, as opposed to the second ascent, which was performed with the help of one of the three visualizations or the human instructor. This assured that no personal bias towards a visualization was introduced. When comparing the two ascents, we assessed how well the participant adopted the technique demonstrated by the system or the human instructor respectively on a three point scale ranging from *(1) no improvement* to *(3) significant improvement.* We distinguished the three possible values as follows:

1. **no improvement** – no improvement could be observed
2. **slight improvement** – the participant showed some improvement, for example the right orientation or placement of the feet or the right sequence of arm movements
3. **significant improvement** – the participant fully applied the technique, sometimes with loss of neglectable detail (e.g. slight deviations of timing)

Afterward, critical ascents with diverging score were assessed by a third expert and discussed, in order to agree on a mutual rating. The improvements of the participants by technique and by visualization methods are depicted in the tables below.

Technique	**Improvement**
Flagging	M=2.0 (*SD=0.81*)
Outside Edge	M=1.41 (*SD= 0.64*)
Rockover	M=2.20 (*SD=0.60*)
Twistlock	M=1.58 (*SD=0.64*)

Table 6.1: Improvements by climbing technique. (1) no improvement, (2) slight improvement, (3) significant improvement

Visualization	**Improvement**
Human	M=2.09 (SD=0.90)
Life-Size	M=1.45 (SD=0.50)
Glass	M=1.58 (SD=0.76)
Display	M=2.00 (SD=0.58)

Table 6.2: Improvements by visualization. (1) no improvement, (2) slight improvement, (3) significant improvement

When looking at the improvements by climbing technique, it can be seen that *The Rockover* has the highest mean improvement score (*MIS*) while *Outside Edge* scored the lowest. The improvements by visualization technique show that the techniques utilized with the *Human* condition have the highest MIS, closely followed by *Display*. For the *Life-Size* condition we could observe the lowest improvement.

6.6 DISCUSSION

Human Feedback vs. Video Feedback

The participants' feedback indicates that the proposed approach cannot replace the human instructor in its entirety. This is mostly due to the instructor's ability to recognize the mistakes of the novice and to give instant, correcting feedback. To integrate such a feature into an automated system, it would be necessary to recognize the postures of both the video-recorded instructor and the novice while simultaneously converting the deviations into instructions, whether visually as in [149] or as spoken instruction derived from the recognized pose (e.g. "Drop your right knee") as proposed by Ramsay and Chang. However, this goes beyond the scope of this work. The participants confirmed our assumption that in-situ visual feedback eliminates the need for remembering every nuance of the instructor demonstrating an ascent. An interesting perspective on social aspects was also provided by the participants: the use of (automated) visual feedback enables novices to train in solitude, which might also be a desirable feature.

Video Feedback

The participants' ratings of the video feedback methods confirmed our assumption that the life-size projection was rated the best, as it was easy to understand and follow. This can be attributed to the exact match between the recording and the in-place replay. Although displaying a third-person view of the climbers through Google Glass initially seemed promising, as the display is fixed in the climbers' field of view, the participants' feedback contradicted this expectation. Many participants found the image quality of Google Glass insufficient, as they could not clearly recognize nearby holds.

Visual Alignment

When using the augmented third-person view, the alignment between the video and the real world presented the greatest challenge. For Google Glass as the display medium, some participants struggled significantly with switching context and focus between the display and the climbing wall. These issues resulted in an uncomfortable and exhausting climbing experience. While future head-mounted displays may address technical limitations such as higher-resolution screens and more powerful processing units, we believe the context-switching problem will likely persist. Using the projected display as a medium appears to be a good alternative to Google Glass. Despite requiring the climber to focus on a different part of the climbing wall during the ascent, this technique demonstrated high user acceptance. We attribute this to the fixed position and larger size of the projected display. Finally, the life-size projection outperformed the third-person view in terms of ease of perception and reproducibility. Although occlusion remains an obvious drawback, the participants appreciated the unambiguity of the in-place projection. Observations indicated that the life-size projection was most effective in guiding climbers to the next hold.

Improvements

To quantify the improvements of the participants, we calculated the mean of the improvement rating, which we defined as the *mean improvement score (MIS)*. As it can be seen in Table 6.1, *The Rockover* has the highest *MIS*. This could be due to the fact that this specific technique gives the most advantage during an ascent when applied correctly. The *Outside Edge* technique, however, is mostly used to conserve power; thus it's not as vital to use this technique for a successful ascent. When looking at the improvements by visualization technique (see Table 6.2), it can be seen that the *Human* condition has the highest MIS. This indicates that the help of a personal coach is still preferable when it comes to copying a certain climbing move, which is also in line with the results of the interviews. Although the participants rated the *Life-Size* projection the best, we could still observe a higher MIS for both third-person view visualizations (*Display* (MIS=2.0) and *Glass* (MIS=1.58)) than the *Life-Size* condition with a MIS of 1.45. Due to the low sample size, we could not show a significant difference between the different MIS; the results still suggest that from the implemented visualizations, the *Display* condition is beneficial for reconstructing climbing movements.

6.6.1 *Hybrid Feedback*

The main key finding of our study is that none of the proposed visualization techniques is alone an ideal solution to the problem. While displaying the third-person view inside Google Glass seemed to be a viable solution, the participants' feedback suggested that both the context switch and also the need to refocus continuously, proved that assumption wrong.

Another key finding was that the life-size projected video worked best for most of the users. However, a common problem was the blocking of the projection when standing in front of the wall. A context-sensitive hybrid approach could combine the benefits of the life-size projection as well as the projected display: During the approach of the user, the projected display is placed in a way so that it is not blocked by the climber. After the climber reached the wall, the visualization switches to the life-size projection. While the projected display bears the challenge of matching the augmented video to the real world, it could be a good alternative for the starting phase of the climb. At this point in time the cognitive load for the climbers is still low, since they are not fully engaged in the climb yet because they are still standing on the ground.

During the climb, the participants stated that the life-size projection was the easiest to follow, since the matching problem is nonexistent. However, some participants mentioned that they lost track of their surroundings. An intelligent system could recognize these times of confusion and provide the climber again with the projected display, automatically adjusting its position to the user's field of view. This recognition could be achieved by observing the users' behaviors, such as moving their heads in a searching pattern, or by knowing the characteristics of the route, e.g. overhangs or volumes that stick out and might block the view of the climbers. The advantages of both visual feedback methods could be combined while overcoming their disadvantages.

6.6.2 *Limitations*

For this study, we selected a set of climbing movements suited to the physical wall available while ensuring a high variation in motion requirements. However, different climbing movements could yield different results. Furthermore, since in the *Life-Size* condition we used a projection from behind the climbers, it was possible for the participants to occlude parts of the projection with their bodies. While using a transparent climbing wall would have allowed for back-projection, we employed a camera projection unit that can easily be placed in front of any climbing or bouldering wall. This setup enables the practice of not only specific techniques but also specific movements on arbitrary parts of a climbing wall. In the current version of the system, the next one of the video sequences is manually triggered as soon as the climber progresses in the ascent in a Wizard-of-Oz manner. Although we are using a Kinect, which suggests that tracking of the climber is easily possible, the climber almost disappears in the depth video stream when close to the wall. This results in faulty skeletons returned by the Kinect software (see also [115]). The solution to this problem was out of the scope of this work. In [207] Sigrist et al. give an extensive review about augmented visual, auditory, haptic and multimodal feedback in motor learning. They claim that especially for complex tasks, concurrent visual feedback has predominantly been reported to be effective. However, the performance gain which is build up in the acquisition phase is lost in retention test. This is explained by the *guidance effect* [8] which states that continuous feedback during a learning task builds up a dependency to the feedback. In future research this should be taken into account by applying techniques such as faded feedback (see [240]).

6.7 CONCLUSION AND FUTURE WORK

In this chapter, we investigated different feedback methods for demonstrating climbing techniques. We proposed an augmented third-person view, where climbers see themselves with a video overlay of an experienced climber. This view is displayed either on a Google Glass worn by the climber or on a projected display on the climbing wall. Additionally, we provided novices with a full-size video of the instructor, projected in-place on the climbing wall. These approaches address the challenge that novices cannot mimic the instructor's ascent in real-time, as the instructor occupies the wall while demonstrating. To assess the advantages and disadvantages of each feedback method, we conducted a lab study with 12 participants which entailed a semi-structured interview after the tasks and a manual video analysis of the respective ascents. One of our key findings was that none of the visual feedback methods can provide an overall solution for in-situ video feedback by themselves. For this we proposed a hybrid approach which combines the benefits of both, the life-size projection and projected displays. The Google Glass was not seen as viable solution by any participant. In addition, we identified a number of issues that are critical for the design of in-situ video feedback systems, which can be applied to fields other than rock climbing.

For future work, it would be interesting to see how the system could be improved by adding a semantic layer which recognizes the detailed variations between the climbing style of the novices compared to the instructor. These variations could be converted to meaningful real-time instructions for the novice. In addition, the use of virtual reality could leverage the process of explaining a specific climbing problem. An avatar performing prerecorded movements could be observed in a virtual environment including the actual climbing wall.

6.8 CONTRIBUTION TO THE RESEARCH QUESTIONS

This work contributes to **RQ 1** and **RQ 2**.

What are factors influencing the acceptance and willingness of athletes to use a computer-supported assistive system for sports training?

RESEARCH QUESTION 1 Considering the post-trial interviews it can be concluded that social factors and independence play a role in acceptance and willingness to use an assistive system. Regarding independence, participants acknowledged that system feedback offers significant advantages, particularly in its ability to provide visual, in-situ guidance without the need for human trainers to be physically present. Some participants expressed a preference for video feedback over human coaching due to the reduced social pressure: "Maybe some people would feel more comfortable with video feedback because they don't want to embarrass themselves in front of a trainer" and "I can climb at my own pace and don't feel stressed because I am being watched." These statements suggest that such assistive systems are able to create a less intimidating and more comfortable learning environment, eventually enhancing user acceptance, particularly for beginners.

How could computer-supported assistive systems communicate feedback and instructions to athletes during training?

RESEARCH QUESTION 3 The results of this study make a substantial contribution to RQ 3 by investigating how visual feedback strastegies can effectively communicate movement instructions, a high density information, to climbers during training. It explores in-situ feedback mechanisms that allow climbers to learn and replicate complex climbing movements while actively performing the activity. The system introduces two distinct visualization techniques: a life-size in-place projection of an experienced climber's ascent on the climbing wall and an augmented third-person view displayed via Google Glass or a projected display. These visualization techniques lend from both, the ghost and magic mirror metaphor (see Section 3.2, specifically [10, 18, 123, 149]).

The findings emphasize the importance of context-aware feedback delivery. The life-size projection was perceived as the most intuitive and easiest to follow because it provides an exact spatial match of movements, reducing cognitive load. However, occlusion caused by the climber's body was identified as a drawback. The augmented third-person view provided on a projected display also demonstrated high acceptance due to its clarity and fixed positioning, which allowed climbers to focus more effectively. In contrast, feedback presented via Google Glass revealed limitations, including difficulties with context switching, small display size, and refocusing challenges.

The results of the study suggest that for complex sports, it is worthwhile to consider multiple different (visual) output modalities that are adapted to the context instead of relying on a one-size-fits-all solution.

Part III

TECHNICAL CONTRIBUTIONS

The third part of this thesis presents the technical contributions. During the implementation of the artifiacts presented in the previous part, several software systems have been implemented based on necessity (e.g. to conduct online and offline studies) but also to lay the foundations for future studies. While not accompanied by full userstudies, the systems nevertheless contribute to the research questions posed in this thesis. In the following, we will present two systems aimed at enabling future studies of real-time feedback systems. Chapter 7 details on a toolkit for rapid prototyping of foot-based feedback systems. In Chapter 8 we present the iterative development process of a virtual reality system allowing for physical climbing on both, a static and a rotating climbing wall while being immersed in a virtual environment. We envision the use of this platform in future investigations of novel real-time feedback methods that are not restricted to physical limitations of the real-world.

7 PROTOTYPING FOOT-BASED FEEDBACK SYSTEMS USING OFF-THE-SHELF PRESSURE SENSORS

This chapter introduces the use of off-the-shelf pressure sensors in combination with a microcontroller for rapid prototyping of foot-based feedback systems. First, we present the implementation and then outline how an improved version was employed in a MobileHCI tutorial to enable participants to build their own gait trainer. This chapter contributes to **RQ 2**. Parts of this chapter have been previously published in the following publications.

Felix Kosmalla, Frederik Wiehr, Florian Daiber, Antonio Krüger. "Using Off-the-shelf Sensors for Ad-hoc Smart Sole Prototyping". *In: Proceedings of the ACM UbiComp Workshop on Ubiquitous Computing in the Mountains (UbiMount).* UBICOMP'16, Germany [132]

Florian Daiber, **Felix Kosmalla**. "Tutorial on Wearable Computing in Sports". *In: Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services.* MobileHCI '17, Austria [42]

7.1 INTRODUCTION

In the previous chapters, we emphasized the importance of maintaining good form in sports to reduce the risk of injury, to improve movement efficiency and to ultimately enhancing the overall sports experience. As examples, we explored rock climbing and slacklining. In slacklining, we utilized vision-based full-body tracking as input for an interactive feedback system. While this approach captures the movements of the entire body, it lacks the ability to detect fine-grained nuances, such as foot pressure distribution during balancing or walking on the slackline. Integrating such detailed measures into interactive systems could enable more holistic feedback for athletes in relation to applied foot pressure or shifts in the center of gravity. This concept has been demonstrated in domains such as weightlifting [56, 57], running [97], and general gait analysis and rehabilitation [120, 234, 245]. A central aspect among these systems is the unified need for real-time feedback tailored to specific use cases. Developing and testing novel feedback methods often includes user studies to evaluate the effectiveness of chosen modalities. While it is possible to trigger feedback manually during wizard-of-oz experiments, providing automated feedback based on participant movements is generally more desirable. Commercially available smart insoles could theoretically serve

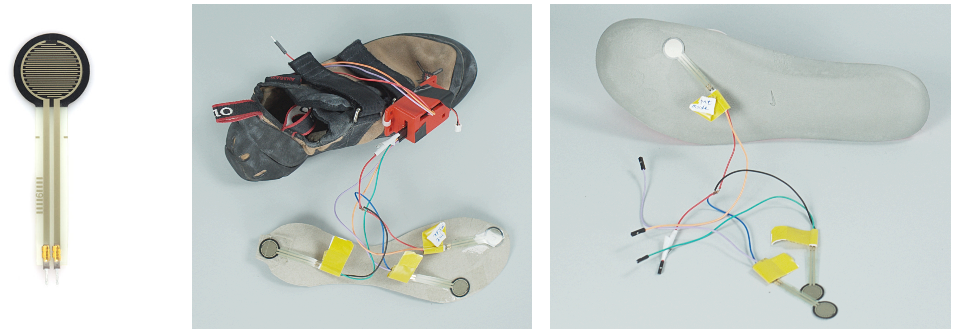

Figure 7.1: Ad-hoc smart insole applications: (Left) FSR-based sensors; (Middle) Cardboard cutout insole for a climbing shoe; (Right) Sensors applied directly to a running shoe insole.

as input for such feedback systems. However, these solutions are sometimes limited by their sensor distribution, data resolution, or cost, which may exceed the budget allocated for a research project.

To increase the accessibility of conducting research in novel real-time feedback methods, in this chapter, we introduce a platform for rapid prototyping of foot-based feedback systems using affordable, off-the-shelf components. In two iteration cycles, we implemented a toolchain, consisting of hardware and software that allows for ad-hoc experiments with flexible, wireless smart insole. During development, we prioritized accessibility, aiming to make the platform approachable for a wide audience, avoiding specialized soldering equipment (such as reflow ovens or heat guns) or custom printed circuit boards. Our overarching goal was to enable researchers and practitioners to build, test, and iterate on interactive feedback systems that provide rich, real-time insights into movement quality without requiring a strong background in embedded systems engineering. We demonstrated this approach through an in-person tutorial, where participants utilized inexpensive hardware, open-source software, and straightforward assembly methods to implement a running assistant inspired by the work of Hassan et al. [97]. In the following sections, we describe the iterative development of the platform and showcase how it could be applied in future research.

7.2 IMPLEMENTATION APPROACHES

Using sensors in gait analysis for physical therapy and orthopedics has a long tradition. To enhance sensor functionality while minimizing bulkiness, various sensing approaches have been explored in past research. A wide range of pressure sensors are based on materials such as Velostat/Linqstat[1], which change their resistance when pressure is applied [54]. These sensors are typically implemented by placing the resistive material between two (possibly flexible) electrodes. The resistance between the two electrodes can be measured using a microcontroller and a simple voltage divider circuit [103]. When pressure is applied, the

1 https://www.adafruit.com/product/136

resistance of the middle layer decreases, resulting in a measurable change that corresponds to the applied pressure. This working principle is employed by FSR, which have been used in the past for smart insoles [158, 217, 234]. For example, Tabrizi et al. [217] embedded FSR based sensors in silicon-molded insoles, connecting them to a battery-powered micro-controller with an additional Bluetooth module. Similarly, Wang et al. [234] followed this approach but in addition to the pressure sensors, but enhanced it with a 3-axis gyroscope and accelerometer to capture the flight phase, i.e., moments when the foot is not touching the ground. Even more sensors were integrated in an insole by Morris and Paradiso [158]. In addition to pressure and motion sensors, they also added bending sensors to meassure the flexion of the insole as well as capacitive and sonar sensors to get insights about the distance from shoe to ground. Their initial results demonstrated the system's ability to detect changes in foot motion during various types of gait, such as slow and fast walking, as well as shuffling. Although the sensor system provides a large amount of sensor data the weight of 200g may severely affect the natural gait of the user.

While the works above utilized prebuilt FSR based sensors, Xu et al. [245] composed their pressure sensitive insole by using conductive textiles. Their design featured a three-layer setup, combining two zebra textiles[2] separated by a layer of Velostat. The zebra textile consists of alternating strips of conductive and non-conductive material, forming a zebra-like pattern. When the three layers are stacked with the zebra textiles arranged perpendicularly, they create a grid divided by the Velostat layer. By addressing each conductive textile strip individually, the intersections form discrete pressure sensors. However, this approach requires individual wiring for each strip, and as the resolution of the grid increases, so does the complexity of the wiring.

Although these prior works are suitable for the applications they propose, we argue that many are too sophisticated, too expensive, or insufficiently flexible for ad-hoc prototyping of proof-of-concept real-time assistive systems.

7.3 BASIC IMPLEMENTATION OF THE PLATFORM

Instead, we are proposing a platform for ad-hoc prototyping of sensor augmented insoles. While there are existing several commercially available sensor insoles, our platform consists of "off the shelf" hardware that is readily available online and has minimal deployment overhead When designing the platform, we aimed for it to be:

1. Fast and easily deployable,
2. reusable, and
3. simple enough to be adapted to the individual purpose.

2 https://www.hitek-ltd.co.uk/product/zebra-fabric/

The first iteration of the insole toolkit used an RFDuino[3] as the processing unit. Although discontinued, the RFDuino was a small Arduino-compatible[4] microcontroller with Bluetooth Low Energy (BLE) capability. This enabled the streaming of sensor data directly to another BLE-enabled device, such as a smartphone or PC. With its six GPIO pins, the RFDuino could read data from up to six FSR-based sensors. In addition to the microcontroller, only a $1k\Omega$ resistor for each sensor and a battery were needed to create a fully functional set of sensors that could be taped to a (cardboard) insole. A simple firmware was implemented for the microcontroller to continuously stream the sensor data as a byte array to any BLE-compatible device. To facilitate rapid prototyping, we developed a small Python client that enabled real-time data analysis (see GitHub[5] for software and hardware documentation).

Using a perfboard, the microcontroller, $1k\Omega$ resistors, and sensors (see Figure 7.1, left) were connected as depicted in Figure b.1. For existing insoles, such as those in running or hiking shoes, sensors could be easily attached using their peel-and-stick rubber backing (see Figure 7.1, right). When shoes do not include (removable) insoles, such as climbing shoes, a custom-fitted cardboard insole proved to be an effective alternative (see Figure 7.1, middle).

7.4 IMPROVING THE PLATFORM FOR A TUTORIAL ON WEARABLE COMPUTING IN SPORTS

In a next step, we extended on the first version of the platform by updating the processing unit and simplifying the communication protocol. While still using the same pressure sensors, we switched from the RFDuino to the popular ESP8266[6] which has inbuilt Wi-Fi capabilities. Using Wi-Fi allows for using communication methods like websockets, which are easier to implement as opposed to dealing with the sometimes tricky process of subscribing to BLE characteristics. Additionally, websockets provide integrations for nearly every programming language and platform. One drawback of the ESP8266 is its limited number of analog inputs, which are needed to measure the resistance of the sensors. To address this, we incorporated an analog-to-digital converter (ADC) breakout board[7], which interfaced with the microcontroller and allowed for up to four pressure sensors. In addition to the sensors, we included a driver for a small disk vibration motor to enable tactile output. The cables for the sensors and vibration motor were equipped with plugs to facilitate easy assembly. The microcontroller, ADC, motor driver, and sockets for the sensors and motor were soldered onto a perfboard. Finally, a custom 3D-printed enclosure was created to neatly house all the electronics.

3 https://github.com/RFduino/RFduino
4 https://www.arduino.cc/
5 https://github.com/felixkosmalla/sensor-insole-prototyping
6 https://www.espressif.com/en/products/modules/esp8266
7 https://www.adafruit.com/product/1083

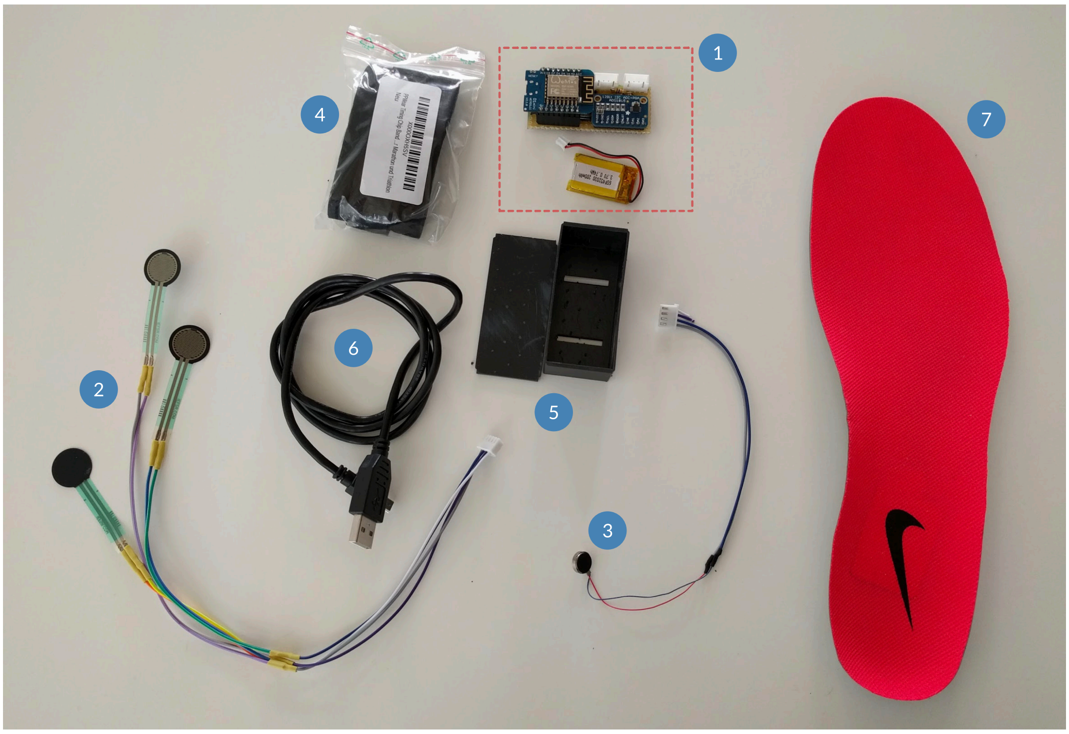

Figure 7.2: Contents of the insole toolkit used in the tutorial. (1) Microcontroller and ADC mounted soldered on a perfboard. A rechargable battery was used to power the electronics. (2) Pressure sensors soldered to a plug. (3) Vibration motor soldered to a plug. (4) Flexible strap to attach virbation motor to the ankle. (5) 3D printed enclosure. (6) Cable to program the microcontroller (7) Running shoe insole. Left: Force Sensing Resistor based Sensor. Middle: A cardboard cutout used as insole for a climbing shoe. Right: Sensors applied directly to the bottom of a running shoe insole.

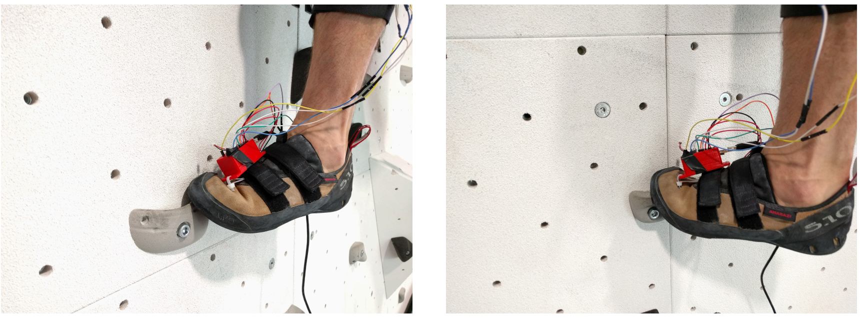

Figure 7.3: Climbing shoe with ad-hoc smart insole.

This new platform was then used in a tutorial on wearable computing in sports [42]. In the tutorial, we introduced participants to wearable computing in sports and the unique challenges involved in designing wearable sports technologies. The target audience included practitioners and academics interested in the intersection of mobile computing and sports. After providing a broad overview of wearable sports technologies, participants engaged in a hands-on activity. In this activity, they were guided to reimplement a simplified version of a forefoot running assistant as demonstrated in [97]. The goal was to detect whether a runner touched the ground with their heel or forefoot first. If a heel strike was detected, the vibration motor was briefly actuated to remind the runner to strike with their forefoot. Participants were provided with the platform components (see Figure 7.2), which included the electronics with an enclosure, a Velcro strap to attach the vibration motor to the ankle, and a running shoe insole. Additionally, initial source code for the microcontroller was supplied, allowing participants to work directly with the sensor data. This code handled essential tasks such as setting up the Wi-Fi access point, reading the sensor data, and streaming it via WebSocket.

As a first step, participants were instructed to assemble the components and attach the sensors to the insole. A small local website was provided to visualize the real-time sensor data streamed from the microcontroller via WebSockets over Wi-Fi. This initial visualization offered participants sufficient insights to implement a simple threshold-based logic to actuate the vibration motor when a heel strike was detected.

Through this process, we introduced participants to the fundamentals of wearable computing in an approachable and practical manner.

7.5 FUTURE APPLICATIONS FOR AD-HOC SMART INSOLES

While we successfully applied the platform in a tutorial, future work could leverage this platform to prototype real-time feedback systems for a variety of sports.

rock climbing In climbing, a smart sole can be used to train foot technique. Although discussions about climbing technique often emphasize upper body strength, learning to optimally place and weight the feet reduces strain on the forearms and helps climbers achieve better positions to efficiently reach the next holds. Precisely matching foot placements (i.e., stepping correctly on footholds without repositioning) conserves energy and increases the likelihood of successfully completing a route. A smart sole can detect weaknesses in foot technique, such as slipping or frequent repositioning of the feet on the same hold. By using a simple tracking mechanism, climbers can gain better awareness of their foot techniques. For example, we deployed sensors on a cardboard insole placed inside a climbing shoe (see Figure 7.3). In an initial test, the system successfully recognized whether the climber used the tip or side of their shoe.

hiking Hiking in mountainous areas often requires confidence and sure-footedness, especially in steep terrain. In this context, feedback systems could alert hikers to increases in slipping or involuntary tilting of the foot, which may indicate extended fatigue. Receiving such feedback could encourage hikers to take a break, helping them recover before safely continuing their descent. Additionally, a smart insole could detect uneven weight distribution, which might suggest improper posture or a developing imbalance due to muscle fatigue. This information could help hikers adjust their stance or pace to maintain stability and prevent injury.

golf In golfing, a pressure-sensitive insole could provide detailed feedback to improve balance and weight transfer during the swing. Proper weight distribution is critical for achieving consistent, powerful shots, and a smart insole could detect imbalances between the front and rear foot or shifts during the backswing and downswing phases. The system could provide real-time cues if a golfer leans too far forward or backward, ensuring a more stable stance, similar to the systems presented in Section 3.2.

7.6 conclusion

This chapter demonstrated the potential of using off-the-shelf pressure sensors to prototype foot-based feedback systems for various sports and physical activities. By developing an accessible and flexible platform, we enabled researchers and practitioners to quickly create and test interactive systems without requiring extensive expertise in embedded systems engineering. Through iterative improvements, the platform evolved to incorporate advanced features like WiFi-based communication and tactile feedback, making it even more user-friendly and versatile. The platform's viability was demonstrated through its use in a tutorial on wearable computing in sports.

7.7 CONTRIBUTIONS TO THE RESERARCH QUESTIONS

What are effective methods for tracking and assessing movements to inform real-time feedback development and testing in a sports context?

This work contributes to **RQ 2**.

RESARCH QUESTION 2 The proposed toolkit introduces a flexible, low-cost foundation for tracking and assessing foot related movements in climbing and other sports using smart insoles. The system leverages off-the-shelf force-sensitive resistors embedded in cardboard insoles to capture pressure data in real time. By using wireless micocontroller units it is possible to stream real-time data to a computer which allows for fast protoyping cycles since it is not needed to program the MCU directly. This makes the toolkit more approachable for researchers having limited experience with embedded computing. Using the toolkit allows for easy exploration of foot pressure related feedback systems such as in climbing, running, hiking, or other sports.

8 CLIMBING IN MIXED REALITY

In Chapter 6, we investigated different real-time in-situ visualizations of climbing movements. To deliver these visualizations, we experimented with different augmentation methods. Two of those used a projector to display content directly on the climbing wall: a life-size in-place projection demonstrating climbing moves allowed for simultaneous climbing and observation while a projected display in the line of sight of the climbers would show them from a third-person perspective superimposed by a trainers recording of a movement. While we found that both methods improved the climbing technique of the participants, none of the methods was without drawback. One limitation was the two-dimensional nature of a projection. In this chapter, we introduce a system that allows for immersive climbing experiences in Virtual Reality. Using this system allows a user to climb on a physical climbing wall while being immersed in a virtual environment. While this chapter does not include any empirical studies, we lay the foundation for future investigations of real-time feedback systems that are not bound to the physical limitations of the real world. We report on the iterative implementation of a virtual reality rock climbing systems that allows to climb on both, a physical, stationary wall, as well on a rotating climbing wall which allows for unlimited vertical motion. The chapter is concluded with an outlook to future studies that have now become feasible.

This chapter contributes to **RQ 3**. Parts of this chapter have been previously published in the following publications.

Felix Kosmalla, André Zenner, Marco Speicher, Florian Daiber, Nico Herbig, Antonio Krüger. "Exploring Rock Climbing in Mixed Reality Environments". *In: Extended Abstracts of the 2017 CHI Conference on Human Factors in Computing Systems* CHI'17, USA [134]

Felix Kosmalla, André Zenner, Corinna Tasch, Florian Daiber, Antonio Krüger. "The Importance of Virtual Hands and Feet for Virtual Reality Climbing". *In: Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* CHI'20, Virtual [135]

Felix Kosmalla, Florian Daiber, Antonio Krüger. "InfinityWall–Vertical Locomotion in Virtual Reality using a Rock Climbing Treadmill." *In: Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* CHI'22, USA [129]

8.1 INTRODUCTION

In the previous chapters, we have emphasized that rock climbing has developed from a dangerous mountaineering adventure exercised only by a few specialists to an easily accessible leisure activity. Today, numerous climbing and bouldering gyms offer a pastime activity, that requires very little preparation and can be done after a day at work to unwind. Recently, indoor rock climbing was augmented by computer systems which aim to enhance the experience of the climber (see Section 3.3.1.1). Besides these physical alterations of climbing walls, rock climbing also found its place in computer games. This includes simple smart-phone games to more sophisticated virtual reality experiences like *The Climb*[1]. The latter allows the player to explore remote areas with a scenic view in an immersive virtual environment (VE) through a head-mounted display, allowing for higher degrees of immersion than playing on a mobile device or desktop computer. Such VR experiences got possible due to the recent development in consumer VR technology. The increasing power and decreasing price of powerful graphics cards, display technology, and tracking solutions made immersive VR available and affordable for the masses and thus paves the way for new game concepts and novel types of applications and interactions. However, the degree of immersion is determined by the expression of the three feedback dimensions: visual, auditory and haptic. While today, the visual and auditory feedback are already very sophisticated, realistic haptic feedback is still one of the next big challenges for VR and a very active field of research [248]. Insko et al. [105] presented a concept of passive haptics, a low-cost approach which can provide realistic haptic impressions. Here, physical objects in the user's real environment, called proxies, are spatially registered with virtual counterparts and provide natural haptic feedback when the user touches them. This feedback can drastically increase the user's sense of presence and enhance spatial learning [105].

While *The Climb* comes closest to climbing in VR, it is lacking exertion and haptic feedback. The work presented in this chapter aims to bridge the gap between climbing in a virtual reality and climbing on a physical wall. In this chapter, we present the iterative process of the development of a virtual reality rock climbing systems that allows to climb on both, a physical, stationary wall, as well on a rotating climbing wall which allows for unlimited vertical motion. We will go into detail of how different technological challenges have been met with the ultimate goal to allow for seamless physical climbing in a virtual environment. This not only allows for novel immersive experiences but also paves the way for the investigation of new feedback methods that are only possible in a virtual environment.

This chapter is organized as follows. First we describe how physical objects have been integrated in virtual environments in the past, providing insights when integrating a physical rock climbing wall into the virtual environment. Next, we introduce the *Climbing Reality Continuum*, classifying this work in a two-dimensional continuum defined by the

1 https://www.theclimbgame.com/

Reality - Virtuality Continuum [155] and t the dimension of virtual versus classical rock climbing. This is followed by the description of the iterative development process of the virtual reality rock climbing system presented in this chapter. Finally, we discuss various past applications, propose several potential future research directions, and conclude the chapter with the contributions to **RQ 3**.

8.2 BACKGROUND AND CONTEXT

In Section 3.2.4 we introduced the Reality - Virtuality continuum, first presented by Milgram and Colquhoun [155]. It represents a taxonomy that classifies systems based on their real and virtual aspects, spanning a continuous space of *Mixed Reality* between the two poles *Reality* and *Virtuality*. While *Reality* represents the world we live in, in *Virtuality*, all our senses would theoretically be stimulated by pure virtual inputs. Systems that augment primarily real content with some virtual stimuli are classified as *Augmented Reality*, and conversely, when real inputs augment the primarily virtual stimuli, a system is classified as *Augmented Virtuality*. Thus, the experience we introduce in this chapter can be classified as *Augmented Virtuality*, as the user's stimulation is primarily virtual (visuals & audio), augmented with passive haptic feedback.

Passive Haptic Feedback in VR

The concept of passive haptic feedback is an established way of introducing haptic feedback to immersive VEs [36, 105, 144, 151, 209]. Here, proxies (i.e. physical counterparts representing virtual objects) are used to provide tactile and kinesthetic feedback. Often, proxies are low-fidelity props made out of cheap and available material such as styrofoam, cardboard, or wood. However, concepts that utilize existing objects in the real surrounding as proxies, exist as well, e.g. the concept of *Substitutional Reality* [209]. Through spatial registration with virtual counterparts, these proxies provide tangibility for objects in the VE. Insko [105] showed that passive haptics can enhance the user's sense of presence. We utilize this to enhance climbing on an artificial climbing wall.

Climbing Reality Continuum

We extended Milgram and Colquhoun's [155] Reality - Virtuality continuum, by introducing the *Climbing Reality Continuum* that classifies climbing activities and applications based on the authenticity of the climbing experience. Figure 8.1 shows the resulting two-dimensional design space combining the *Reality - Virtuality* continuum and the *Climbing Reality* continuum. The *Climbing Reality* continuum spans from pure *virtual climbing* on one end to

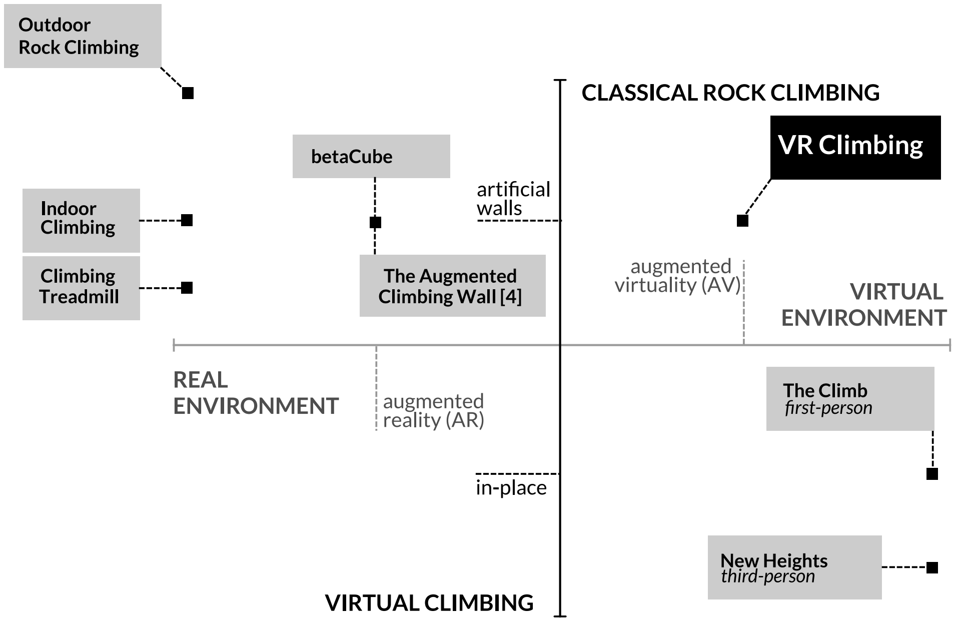

Figure 8.1: Two-dimensional continuum spanned by the *Climbing Reality Continuum* (vertical axis) and the *Reality - Virtuality Continuum* [155] (horizontal axis) with some examples. Our VR climbing system is located in the upper right quadrant.

outdoor rock climbing on the opposite end. This results in four quadrants which will be addressed below, following a counterclockwise order.

CLASSICAL ROCK CLIMBING IN A REAL ENVIRONMENT Here, commonly known climbing activities take place. This includes climbing in the outdoors or, moving closer to the bottom end of the continuum, climbing on an artificial climbing wall. So-called climbing treadmills that allow for in-place vertical ascents, could be placed even closer to *Virtual Climbing*. In this quadrant, climbing experiences such as the *betaCube* [237] and the *Augmented Climbing Wall* [114, 116] can be located. Both systems use projections on the climbing wall to show recordings of past climbs and game elements directly on the physical climbing wall.

VIRTUAL CLIMBING IN A REAL ENVIRONMENT This quadrant is currently under-explored. Here, one could find entertainment or training systems where a virtual avatar is projected onto a climbing wall while a player controls the climbing movements of this avatar.

VIRTUAL CLIMBING IN VIRTUAL ENVIRONMENTS Here, games and simulators would be located. Games played on a screen and controlled with mouse, keyboard, or gamepad such as *New Heights*[2] allow players to control a virtual avatar seen from a third-person perspective during an ascent of a virtual wall. These third-person climbing simulators are located closer to the *virtual climbing* end of the spectrum. If the player, however, is immersed through an HMD and can climb by grabbing virtual grips with motion-tracked controllers, while moving the arms to virtually pull up the body, the interaction is more related to actual climbing. These *first-person* simulators are located closer towards classical rock climbing.

CLASSICAL ROCK CLIMBING IN A VIRTUAL ENVIRONMENT Finally, this quadrant gives room to experiences that we enable with the system presented in this chapter. Here, climbers can actually climb on a physical climbing wall while being fully immersed in a virtual environment. To not break immersion, a strong coupling of physical world (climbing holds and wall) and virtual environment (digitized versions of holds and wall) needs to be established.

8.3 FIRST ITERATION | HAND VISUALIZATIONS AND BYSTANDERS

In a first iteration, we focussed on an immersive climbing experience, that, after putting on the HMD, would place the climber in front of a virtual climbing wall placed on the face of the Matterhorn, one of Europe's highest mountains. The virtual climbing was a replica of the physical climbing wall and positioned so that the features of the physical wall aligned with its virtual counterpart.

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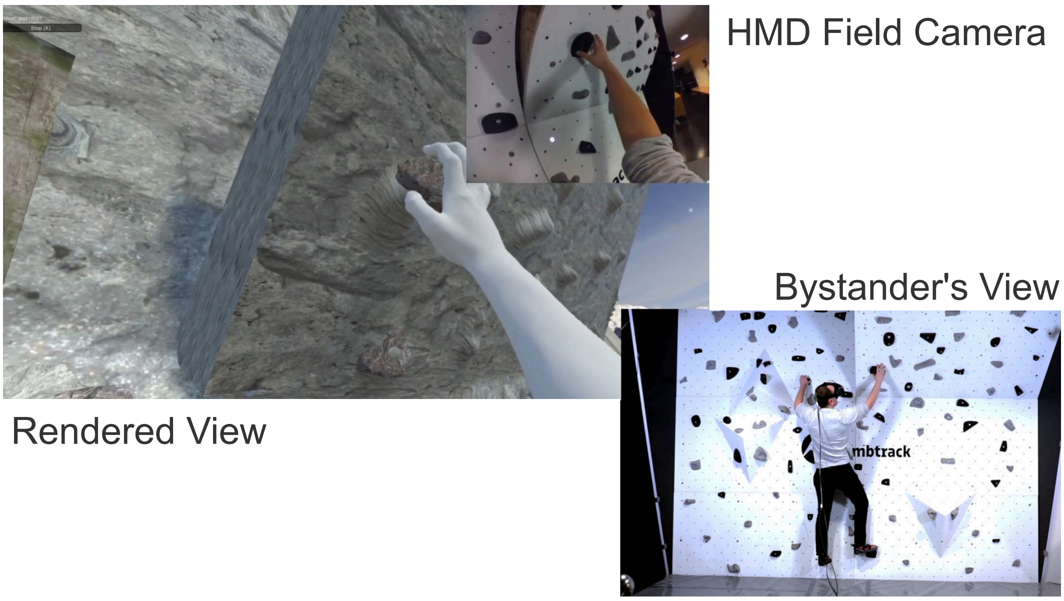

Figure 8.2: Visualization of the virtual reality climbing system. The integrated field camera of the HTC Vive was used to capture the view that the climber would have seen.

2 https://tinyurl.com/3p4eykmt

8.3.1 *Setup*

The setup of our VR climbing prototype consists of an artificial climbing wall with $4m$ in width and $3m$ in height that included an overhanging panel and three volumes (see Figure 8.3, left). To catch the climber in case of a sudden fall, a thick mat covers the floor in front of the climbing wall. For the VR headset, we opted for the HTC Vive headset, since it allows for free movement within a certain area and high quality position tracking. The system we used consisted of the headset itself, two controllers, and two *lighthouses* that are needed for tracking. In this iteration, we placed the lighthouses to the right and left of the climbing wall in approximately $2.5m$ height. For the hand tracking, we mounted a Leap Motion[3] controller on the headset. The Leap Motion controller was orginally presented as desktop input device for midair hand gestures. If placed on the HMD facing away from the wearer, it could also be used to track and thus visualize the hands of the user, including singular finger movements. By the time of implementation, Vive trackers were not available yet, thus in this prototype, foot tracking was not available. This, and all furhter implementations were done with Unity 3D.

8.3.2 *Virtual Environment*

As a first step, we scanned the climbing wall with the help of a Kinect v1 and the *Skanect*[4] software. After cleaning up the model in Meshlab, by removing unneeded parts and reducing the number of faces, we imported the model into a Unity scene. For our prototype, we used a height map of the Matterhorn that was applied to a terrain. The 3D model of the climbing wall was placed at the top of the mountain to give a feeling of height. As an entry point for the climber, we added a virtual wooden ledge on which the climber would find herself when putting on the HMD.

As opposed to common VR games where a registration in the physical playing environment is not necessary (except for the position and orientation of the floor), the calibration of the virtual and the physical environment is critical for climbing in VR. The positions of the virtual holds have to match the physical holds exactly, otherwise the climber would grab into the air or hit the climbing wall with the hands.

For this, we implemented a simple calibration method: In the first step we defined four *calibration points* on the climbing wall that are easily identifiable in both the 3D model and the physical wall. In our case, we chose the tips of the three volumes (see Figure 8.3) and one additional hold. These four points were then registered in the Unity scene by placing invisible *game objects* at the respective positions on the 3D model of the climbing wall. In a second step we used one of the Vive controllers to register the positions of the calibration points in Vive / physical space. As a result we had four coordinate pairs. In a last step, we

3 https://tinyurl.com/2mxvbrps
4 http://skanect.occipital.com/

calculated the optimal rotation and translation applied to the Vive space using single value decomposition to match the model of the climbing wall. We provide a sample Unity project with a manual on how to create custom virtual environments matching a physical scene on GitHub[5]. This project can also be used for applications beyond the scope of this work.

Figure 8.3: Calibration of physcial and virtual climbing wall. Easily identifyable feauters such as climbing holds and tips of wooden volumes were used as point-pairs between physical and virtual climbing wall.

8.3.3 *Projection*

As an optional feature we used the Microsoft Room Alive Toolkit[6] and the corresponding Unity Plugin[7] to create a mixed reality experience. This toolkit allows for seamless projection mapping, which we used to project the virtual environment onto the physical climbing wall. For this, we used a camera projection unit as in the work by Wiehr et al. [237], which was placed in front of the climbing wall. The Unity plugin was used to place a virtual camera in front of the 3D model of the climbing wall, with intrinsic parameters equivalent to those of the used projector. With this setup, a virtual object such as a sphere placed on the virtual climbing wall would be projected in 2D directly on the climbing wall at the corresponding position. Since the VR view in the HMD was rendered on a different machine than the projection, we synchronized the two views via the multiplayer SDK of Unity. This setup allows for seamless projection mapping form the virtual environment seen by the climber onto the physical climbing wall (see Figure 8.4).

8.3.4 *Climbing Game*

We presented our prototype at our institution's Christmas event. Since we did not expect every user to be a climber, we implemented a small game in which the player had to collect

5 https://github.com/felixkosmalla/unity-vive-reality-mapper
6 https://github.com/Kinect/RoomAliveToolkit
7 https://github.com/Superdroidz/UnityRoomAlive

Figure 8.4: Climbing in virtual reality with a visualization of hands using the optical tracking of the Leap Motion. The virtual environment is projected back on the physical climbing wall to reflect the interactions of the player in the VE.

as many presents as possible by touching them with their hands. The players had to step on two marked foot holds and as soon as they grabbed a third hold with their hands, the game started. To include the audience, we used the projected mixed reality as described above (see Figure 8.4). Here, we also implemented a bidirectional communication method in form of a virtual flashlight. Bystanders could point a Vive controller towards the climbing wall which would then shine a virtual light onto the wall which could be seen in both, the virtual and physical world via the projection.

Figure 8.5: Climbing on a static wall in VR with visualized hands and feet. Tracking was achieved by using Vive trackers attached to hands and feet.

8.4 SECOND ITERATION | ROBUST TRACKING OF HANDS AND FEET

While the first iteration demonstrated the feasability of the approach, opportunities for improvement were highlighted. Since we used the Leap Motion to track the hands of the user, the hands could only been rendered when in the viewfield of the Leap Motion. This was only a minor problem, since if the hands of the user were not in the field of view of the Leap Motion, then they were also not in the field of view of the HMD, thus the missing rendering was not noticiable in most cases. However, the tracking had to be reestablished everytime the field of view changed so that the hands came back into sight again. If hands were currently gradbbing a handhold, tracking quality degraded. Furthermore, tracking of feet was not supported in the first iteration.

The aim of the second iteration was to integrate a robust tracking of both, hands and feet. For this we used the Vive trackers which were then becomming available.

Figure 8.6: Wooden template to calibrate the climbers hands and feet with their virtual counterparts. Left: physical template, middle: virtual model of the template with 3D models of digitized climbing shoes, right: User calibration his shoe with the virtual counterpart.

8.4.1 *Calibration of Hands and Feet*

While keeping the 3D model and calibration of the physical climbing wall, we extended the previous setup by adding HTC Vive trackers to the top of the climber's feet and the back of their hands to track them. To represent the hands of the climber, we used a prerigged 3D model of virtual hands. For the feet, we digitized a pair of climbing shoes using photogrammetry.

To calibrate the climber's shoes with their virtual counterparts, we crafted a wooden template utilizing a laser cutter and MDF panels as depicted in Figure 8.6 (left). We designed the template so that we could line up both the virtual, and the physical shoes with the horizontal and vertical panels as shown in Figure 8.6 (middle). In addition to that, we added a mount for an HTC Vive tracker. The 3D model of the wooden template was import into the scene and placed in the hierarchy of the Vive tracker. This provided us with the exact position and rotation of the template at all times, allowing for a flexible calibration. Prior to the calibration, the virtual shoes are attached as children of the template so that the sides and tips of the shoes would line up as described above. While wearing climbing shoes fitted with individual Vive trackers, the climbers would be asked to step onto the template (see Figure 8.6, right), lining up their physical shoes as closely to the virtual representation as possible. A press of a button completed the calibration and changed the parent of the virtual shoes in the scene hierarchy to the Vive trackers, resulting in a visualization of the climbers' feet in the virtual environment. This mehtods allowed for flexible placement of the vive tracker on the shoes, regardless of initial position and rotation of the tracker.

The calibration of the hands followed a similar pattern. We attached Vive trackers to the back of the hands of the climbers with velcro straps. Rigged and animated hands were placed palm down and extended onto the same wooden template so that the tip of the middle finger as also the tip of the thumb lined up with the horizontal, respectively the vertical panel. A button press changed the parent of the virtual hands in the scene hierarchy after placing the physical hands onto the template.

Since the use of Vive trackers alone does not allow for sensing individual finger movements, we triggered a closing-hand animation as soon as the hand of the climber came in close range of a climbing hold. Although we recognize that this is just an approximation of the real world, we chose this option over wearing VR gloves to (a) preserve the sensory experience while touching climbing holds and (b) come closer to reality since climbing with gloves is rather uncommon. The resulting first-person view of the climber can be seen in Figure 8.5. Using this setup allowed for the same climbing experience as presented in the first iteration but now provides a more robust tracking of hands and feet.

8.5 THIRD ITERATION | CONTINIOUS CLIMBING ON A CLIMBING TREADMILL

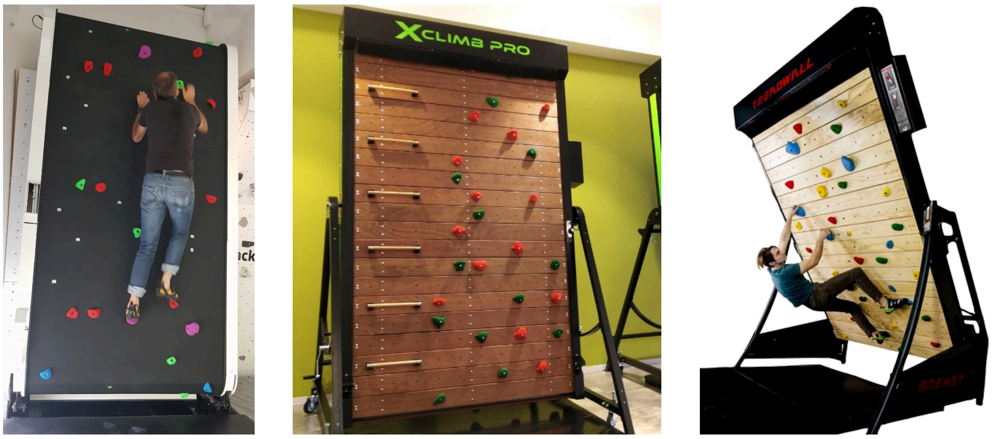

Figure 8.7: Different types of climbing treadmills[8]. From left to right: Climbstation (used in this work), Xclimbpro, Treadwall

Scan QR-Code for Video

With the increasing popularity of rock climbing, new technologies have been introduced in this sport: Multiple vendors offer so-called climbing treadmills. These have a vertical conveyor belts with attached hand and food holds (see Figure 8.7). The mechanics involved move the belt in sync with the climber, allowing for an infinite, albeit repetitive accent, since the climber will be presented with the same holds starting with each new rotation of the belt. While these machines are commercially available, an integration of VR is not available yet. In this third iteration, we detail on the implementation of a system that allows for climbing on a physical climbing treadmill while being immersed in a virtual environment. While we implemented this system for the Climbstation[9], the general concept is applicable for a generic model.

8 From left to right: Climbstation https://www.climbstation.com/, xclimbpro. Image taken from https://xclimbpro.com/, Treadwall. Image taken from https://treadwallfitness.com/.

9 https://climbstation.com/

Figure 8.8: The Climbstation is a climbing treadmill that allows for continuous climbing with a slant from -15 to 45 degrees. We used the Vive VR system to allow for physical climbing in a VE. Vive trackers attached to the frame of the climbing wall track the position and slant of the wall. Three Lighthouse systems were employed, two in front of the wall and one above the wall pointing towards the floor. In the back of the wall, a spring-loaded wheel with a rotary encoder measures the position of the belt.

8.5.1 *Integration of the Climbing Treadmill*

In this implementation, we used a Climbstation, a rotating climbing treadmill. It features a climbing surface of $1.5m$ by approximately $3m$ with a total belt length of $6.4m$. The belt is mounted on a number of aluminum extrusions that run in rails on either side of the climbing treadmill. The extrusions have nuts integrated in them on which standard climbing holds can be fastened Using its actuators, the climbing wall can be tilted while climbing within the range of $+15°$ to $-45°$, allowing for slab climbing or climbing on an overhang. The climbing treadmill has a digital control system that automatically adjusts the speed of the belt according to the climbers accent, on contrast to a running treadmill where the speed is prescribed by the machine. Sensors at the top and bottom of the wall will break or accelerate the belt when the climber is about to reach either end of the wall. While we implemented the system for this specific model, it can be easily adapted for models of other manufacturers. As VR hardware we chose the HTC Vive Pro, leveraging their Lighthouse Tracking System with absolute positions for the HMD and wireless trackers (also see Video Figure[10]). As mentioned before Unity 3D was used as the game engine. In their terminology *GameObjects* are virtual objects that are placed in a *Scene*. If they are placed in the hierarchy of another GameObject, they will follow the translation and rotation of this parent.

To integrate the physical climbing wall into a VR experience, several steps have to be performed, which are described in more detail below. To begin, the location and configuration (i.e. the tilt of the wall as well as the position of the belt) has to be continuously monitored. For this, we used multiples Vive trackers to follow the frame of the climbing wall and custom hardware to measure the position of the belt. Afterward, a virtual model of the climbing wall and its holds has to be created. This includes tooling to digitize climbing holds and to align the virtual models according to their physical counterparts. As a third step, the virtual model from step one has to be aligned according to the data acquired in step two. Finally, a visual representation the user's hands and feet has to be integrated into the VE.

Figure 8.9: Vive tracker mounts with integrated damping

8.5.1.1 *Monitoring the Configuration of the Climbing Wall*

To represent the physical climbing wall in a VE, its configuration (i.e. position of the wall itself, slant, and position of the belt) has to be tracked. The position and tilt of the wall was acquired by mounting three Vive trackers on the border of the frame: two on the top of the frame in equal height and one in the bottom left of the frame. To keep the trackers in place on the frame, we designed custom mounts that feature a quick release mechanism (see Figure 8.9) and flexible dampers to reduce vibration during movement of the belt and change of tilt (see Figure 8.9). This should mitigate possible sensor drift[11].

The three Vive trackers are used to align the virtual climbing surface to its physical counterpart. To achieve this automatically, we used the process described in the iteration above: three or more points that are easily identifiable on the physical wall as well as on

10 https://umtl.cs.uni-saarland.de/research/projects/infinitywall.html
11 https://tinyurl.com/sn6tjeyy

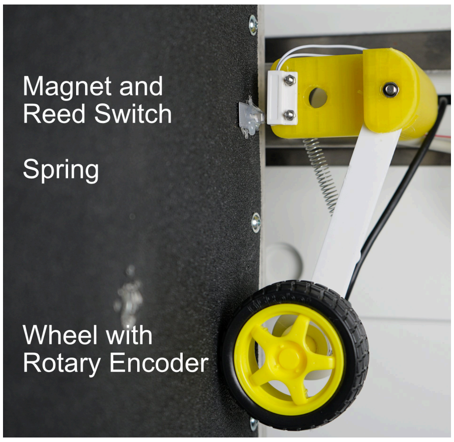

Figure 8.10: We designed a spring-loaded arm that presses a wheel onto the belt of the climbing wall. A rotary encoder mounted to the wheel measures the rotation while a reed switch detects the start of a new revolution of the belt by means of a single magnet glued to the belt.

the virtual model are obtained and by means of Singular Value Decomposition, the optimal rotation and translation is found to align the corresponding points. Running this algorithm continuously will render the virtual frame at the correct position and slant. While the exact position of the trackers is not important, as long as the triangle formed by the trackers is not an isosceles triangle. This is due to the process of aligning the 3D model of the frame with the physical world.

To obtain the three points on the virtual model, the climbing wall is brought to an upright position, perpendicular to the floor with the trackers attached. While running the Unity editor, a (later invisible) cuboid *(belt container)* is manually aligned to the plane that is held by the position of the three trackers. Within the hierarchy of this cuboid, reference points in form of GameObjects are placed for each tracker. Additionally, the cuboid will later on hold the model of the belt itself with its climbing holds. With this, we have a virtual model of the frame with three reference points that spatially correspond to the physical climbing wall. To address the individual Vive trackers, we used the Vive Input Utility Unity package[12]. First trials have shown that placing the two Vive Lighthouses in front and next to the climbing wall and one mounted on the ceiling pointing towards the floor results in a robust tracking of all trackers and the HMD. The Lighthouse mounted on the ceiling allows for both arms pointing upwards while climbing, which would usually result in covering too many sensors of the HMD that could be captured solely by two lighthouses to the left and right of the climber.

After having established the spatial configuration of the frame, the position of the belt has to be monitored. While the Climbstation has a machine-readable interface, the resolution of the belt distance is rather coarse (approx. 5cm per tick), which does not allow for a precise representation in VR. To overcome this issue, we designed and 3D printed a frame holding a

12 https://tinyurl.com/54jhrtpe

spring-loaded wheel that presses on the belt of the climbing wall (see Figure 8.10). A rotary encoder (WISAMIC 600p/r) driven by a Wemos D1 Mini was attached to the wheel to read out the rotations. To reduce drift induced by slipping of the wheel and also to introduce a zero position, a small magnet was glued to the belt which is detected by a reed switch. The current tick count of the rotary encoder and status of the reed switch is printed to the serial output every $16ms$ which is in turn consumed by the Unity application. To convert ticks to meters, an initial calibration has to be performed once for the setup. This is done by mounting a Vive tracker to the belt, with which the distance traveled between two fixed but arbitrary points can be meassured. Simultaneously recording the tick count of the rotary encoder allows for calculating a fixed scaling factor to convert from ticks to meters.

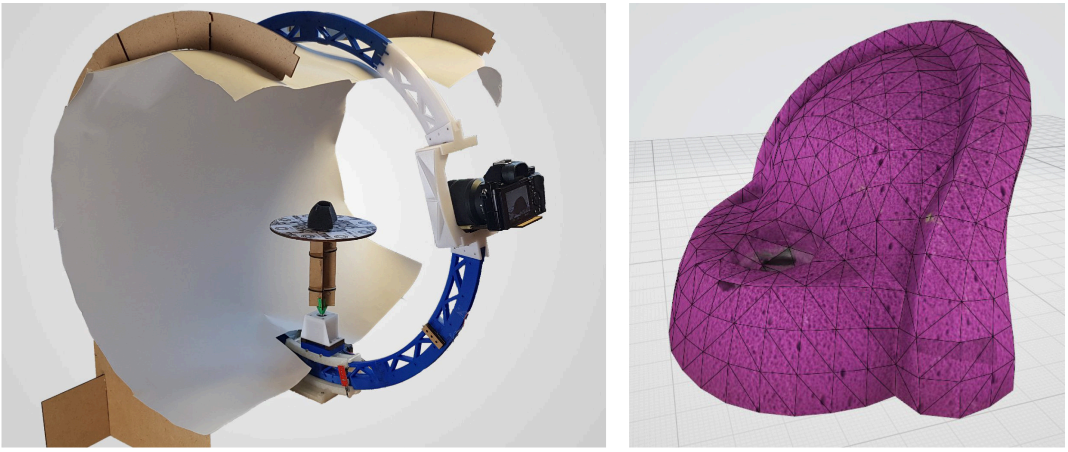

Figure 8.11: We used an open source photogrammetry rig that allows one to take a set of pictures from an object from different angles. These pictures were used in Meshroom to reconstruct 3D models of the climbing holds.

8.5.1.2 *Modeling the Climbing Wall*

While the belt of the climbing wall can be modeled as a simple plane or cuboid, the climbing holds need a more sophisticated representation. Climbing holds come in different shapes and sizes, ranging from tiny footholds with the size of a matchbox, holds that can only accommodate the tip of a finger, to large holds that can be grabbed with the climber's whole hand. The holds are mounted with bolts that are screwed into existing threads integrated into the belt of the climbing wall. To prepare the climber in the VR for the upcoming holds, the virtual models should allow for an assessment of the holds' topology before grabbing it. This reasoning is based on feedback from preliminary experiments in which only very low fidelity models were used. Using these rough models resulted in the climber trying to grab the hold and immediately readjusting their grip since the visual representation did not match the actual physics of the hold. We used an open source turntable[13] design to acquire pictures with a DSLR camera of the individual climbing holds which we then used to create

13 https://openscan.eu/pages/openscan-classic

3D models via photogrammetry (see Figure 8.11). Meshroom[14] was used for the creation of the 3D models. After cleaning the resulting model from artifacts and the turntable base, we reduced the number of polygons using Instant Meshes[109], followed by a re-texturing of the now decimated model with Meshroom. The individual models were converted into pre-configured GameObjects with the origin placed on the ground plane and in the center of the bolthole.

To represent the climbing holds in the VR, a virtual belt in form of a cuboid is placed within the *belt container* and is moved according to the readout of the belt sensor described above. After each full rotation of the belt, it will reset itself to the initial (null) position. Within the hierarchy of this belt, the virtual holds need to be initially positioned. To facilitate this process, we implemented a simple editor (see Figure 8.12). Once the climbing wall has been set up (i.e. physical holds are already mounted), the procedure is as follows: First, the position of the physical hold has to be defined. This is done by placing the bottom of the Vive controller directly on the head of the bolt. A press on a button confirms this position. To obtain the position on the belt (remember: the origin of the virtual holds is located on its ground plane), the end of the Vive tracker is placed on the belt, next to the hold to obtain the exact plane of the belt. In doing so, the position of the thread is obtained. After establishing the base position of the hold to be placed, the user is guided through the process of selecting the corresponding virtual model of the climbing hold. Holds are grouped by color and can also be identified with their number that was established during the digitizing process. After selecting the corresponding virtual hold, the correct orientation of the hold can be set by rotating the Vive controller followed by a press of the trigger to confirm. Finally, the virtual hold is placed within the hierarchy of the virtual belt. To save the setup of the holds, the local position, local rotation, and hold ID are stored in a file.

8.5.2 *Showcase Scenarios*

To demonstrate the possible applications of the system, we implemented two initial showcase scenarios: a virtual representation of the rotating climbing wall in a virtual exhibition room (see Figure 8.13) and a skyscraper climbing simulator in a futuristic city (see Figure 8.13). In the exhibition room demo, we implemented a simple route editor to break the monotony given by the repeating belt. By default, the virtual world shows virtual representations of all physically present holds. The sequence of holds repeats every *pitch* of the belt (rougly every six meters). To break this monotony, using the route editor, holds' visibility can be determined for every pitch, resulting in a varied hold setup that spans extends beyond the physical belt length. Besides creating longer routes, this also allows for visualizing routes of differing difficulty. Routes sharing the same section of a wall is common practice in climbing gyms, with the difference being that holds that belong to a specific route are usually marked

14 https://alicevision.org/

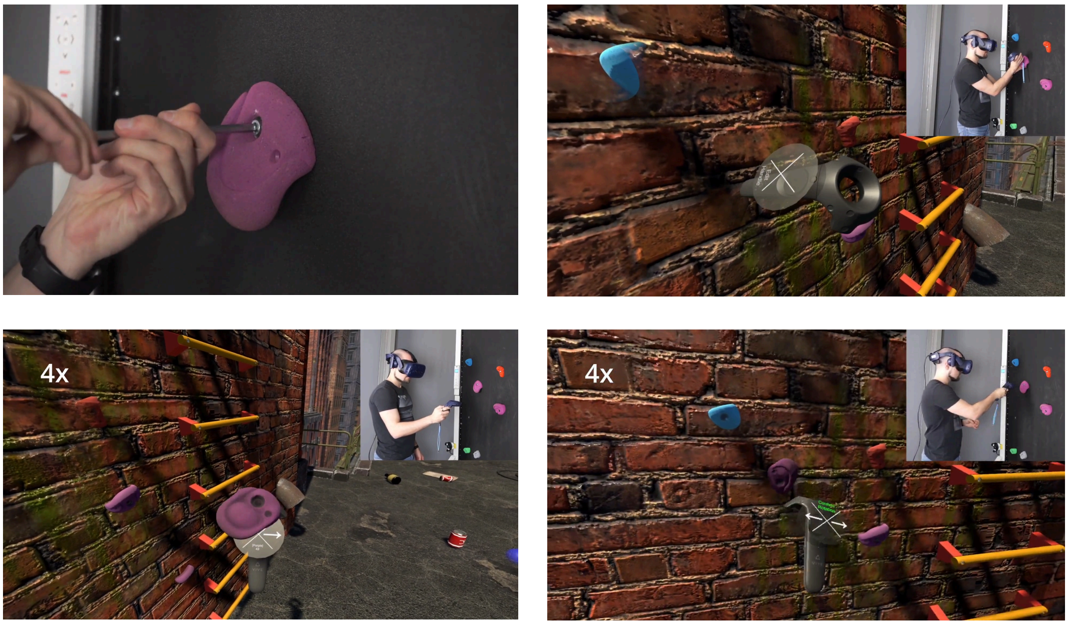

Figure 8.12: We implemented a custom editor to match the virtual holds to their physical counterparts. Based on the physically mounted hold (top left), after registering the position (top right), the virtual model needs to be selected (bottom left), to finally adjust the rotation of the virtual (bottom right).

by the same color or colored tape next to the holds. Hiding holds that do not belong to the current route/repetition should improve the illusion of a long route and give a better user experience.

While the exhibition room showcase demonstrates the capability of replaying a custom route, a feeling of height is not induced since the climber is still displayed near the ground. To leverage the possibilities of VR, we implemented another showcase in which the climber scales a skyscraper in a futuristic city. For this, we attached the complete 3D model of the city to the belt GameObject. Whenever the belt moves down, the city is 'pushed down' as well, resulting in a feeling of ascension. With each new revolution, the city model is detached from the belt, the belt position is reset, and the city model is attached again. This allows for continuous climbing up the skyscraper. To decrease the risk of injury when stopping climbing, a piece of virtual floor is faded-in whenever the climber's feet approach the physical floor to bring back a sense of orientation. While we did not perform a full user study, informal trials have shown that climbing is easily possible, that the location of virtual climbing holds corresponds to the position of their physical counterparts, and that a feeling of height is induced in the skyscraper showcase.

The source code, documentation and CAD models of the project, including the two showcase scenarios, can be found online [15].

15 https://umtl-git.dfki.de/infinityclimb

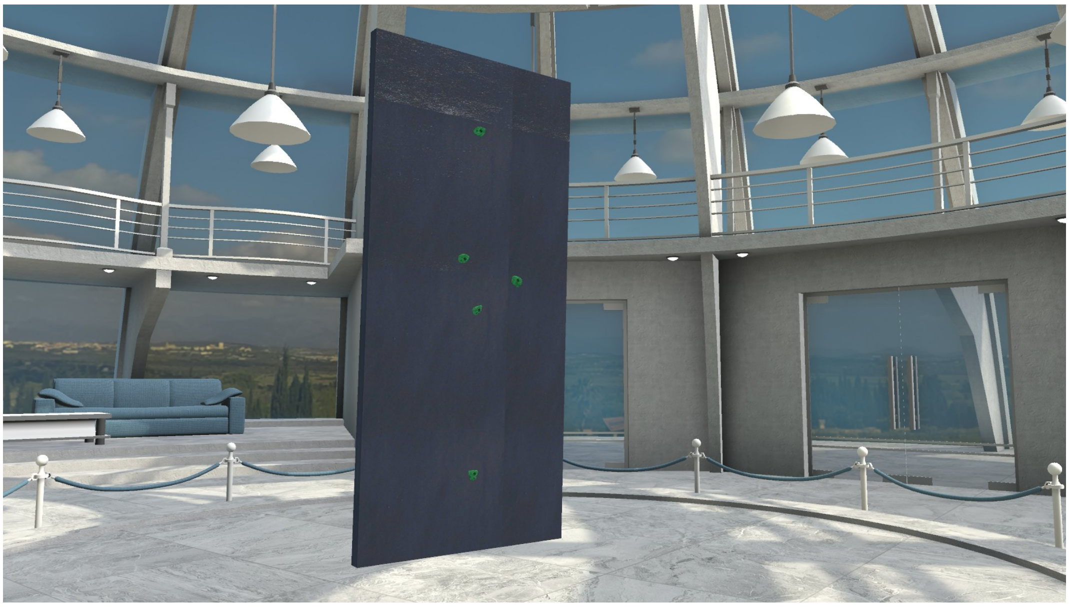

Figure 8.13: The exhibition room scenario features a minimalistic representation of the climbing treadmill. Similar to climbing routes in a climbing gym, only a subset of the available holds will be displayed. This allows for a more varied climbing experience, albeit the repeating belt.

8.6 VIRTUAL REALITY CLIMBING WALLS AS A PLATFORM

8.6.1 *Exploration of Novel Entertainment Experiences*

Both the VR enabled static wall and the climbing treadmill have been extensively used in social events, visits of foreign research groups, or as outreach medium during open house days of the university. Furthermore, we used the rotating climbing wall as platform in a university course focusing on the development of exergames[16]. Small groups of students worked on different concepts revolving around the exergame aspect and including bystanders. As a result, the platform has been successfully used to teach concepts of locomotion in VR as well as mutlimodal user interfaces.

8.6.2 *Initial Experiments on Perception*

Using the static wall, we conducted first experiments on the importance of virtual hands and feet in VR climbing [135]. Motivated by observations during the early development of the first iteration of the prototype, we found that experienced climbers could climb while wearing a headset without seeing either hands or feet. In the study we tested different visual combinations (only hands, only feet, both, none) and collected qualitative feedback.

16 https://tinyurl.com/4j49muju

Figure 8.14: In the skyscraper scenario the climber is immersed into a futuristic city. In contrast to the exhibition room scenario, the climber will ascend a large skyscraper. The holds of one belt revolution are stitched together to allow continuous climbing.

The analysis of the results suggests taht visualizing feet is more critical than hands for an enjoyable and accurate VR climbing experience.

8.6.3 *Future Research Opportunities*

Having a robust platform now allows for different research opportunities ranging from more indepth perception experiments or the investigation of novel feedback methods that defy physical restrictions of the real world.

8.6.3.1 *Perception*

As demonstrated in the skyscraper showcase, the sensation of (extreme) heights can be simulated. This could be used to explore new methods for acrophobia or fear of heights treatment [59], investigate height perception in VR climbing [202], or in general to simulate other tasks in (extreme) heights (e.g. [48]). Furthermore, similar to redirected touching [15], redirected grabbing of climbing holds or the effects of overhang perception could be studied in psycho physical experiments. Combining techniques such as redirected grabbing and the possibility of the climbstation to programmatically change the tilt of the wall could allow climbing popular outdoor climbing routes that were previously digitized with a drone, similar to [236]. Tilting the wall also allows creating interesting shifts of perception by using two different tile angles for the physical and virtual wall. When the physical wall is tilted less than the virtual wall, this might result in a feeling of increased performance since visually the climber is scaling a steep overhang will in reality just a slight negativ incline is rendered. This might result in so-called virtual performance augmentation [106] giving the climber the illusion of greater capabilities than they actually have, ultimately resulting in a hightend confidence.

8.6.3.2 *Novel Feedback Methods*

Using VR allows rendering feedback that would not be feasible due to the physical consraints of the real world.

3D AVATARS Similar to the life-size projection investigated in Chapter 6, a 3D avatar demonstrating climbing movements could be displayed in the virtual environment. Besides overcomming the issue of occluding the projection from behind the climber, the visualization would be upgraded to a three-dimensional one, allowing for better observations of the trainer's movement such as shifting of the weight or twisting of the upper body or legs. Similar to the work by Chua et al. [34], the visualization could include views that show both, the trainee and trainer from different perspectives. This could include a side view, where the climbing wall is replicated to the left and right of the climber or even a mirrored approach where the climbing wall is rendered translucent. Here, the trainee would see the trainer facing them, similar to the mirror metaphor seen in *YouMove* [10] or other training systems for dancing [18, 55, 149].

FLOATING DISPLAYS AND VISUAL AUGMENTATIONS Floating displays or other forms of augmentations could indicate the next, optimal climbing hold. Besides the locations, these augmentations could also give insight about the type of hold which is not always visible when observing from below. This would allow the climbers to prepare themselves for a hold that only allows to place the tips of the fingers. Other visuals could indicate where to shift center of gravity. The use of VR allows placing these indicators strategically within the climber's field of view to provide real-time assistance. Furthermore, it allows altering the representation of the reality by removing elements like holds from the wall or adding new details like weather conditions, animals, or falling rocks in the IVE which could be used to safely experience dangerous situations.

SPATIAL AUDIO Having the head spatially registered in the virtual environment via the HMD allows rendering spatial audio that guides climbers toward specific holds or alerts them to potential errors in their movements. For example, if a climber's foot is misplaced, a subtle sound could be emitted from the foot's location, prompting an adjustment without requiring visual confirmation. *Audio breadcrumps* could be placed along a virtual route that lead the climber sequentially from hold to hold. Here, the holds would emit a specific sound, indicating how it should be used, e.g. with the left hand or right foot.

8.7 CONCLUSION

In this chapter, we presented the iterative development that integrates staic climbing walls as well as climbing treadmills into a virtual environment. We gave insights in how to efficiently create virtual models of climbing walls that are robust enough to be used as haptic proxy when climbing on them while being immersed by wearing an HMD. Furhter, a calibration method has been proposed and published online [17] to align both, climbing walls and virtual hands and feet that can be used beyond the application of VR climbing experiences. The feasability and robustness of the system have been demonstrated in informal trials. Looking ahead, these systems could serve as platforms for exploring future research opportunities, including the study of percpetional aspects and novel feedback methods.

8.8 CONTRIBUTION TO THE RESEARCH QUESTIONS

How could computer-supported assistive systems communicate feedback and instructions to athletes during training?

RESEARCH QUESTION 3 This chapter contributes to the research question by presenting a VR climbing system that serves as a foundational platform for future research. With the focus of this chapter being set on the technical implementation, the platforms presented in this chapter introduces key capabilities that enable the exploration and evaluation of novel feedback strategies. By integrating robust tracking of hands and feet and accurate spatial alignment of physical and virtual climbing walls, the platform could be usder for implementing and testing novel visual, auditory, and haptic feedback modalities. With this, feedback system can be devleoped that decouple physical constraints from experimental design. For example, as shown in Chapter 6, projections have the inherent characteristic that a shadow from the climber hides visual information. By overcoming these physical constraints, the system allows for the exploration of novel feedback mechanisms, such as virtual 3D trainers or floating displays, which would be impossible in real-world settings. Furthermore, having a more computerized environment also facilitates replicable and controlled experimental studies. This can be achieved by automatically rendering a cue at the exact same time between participants or recording performance relevant results through tracking data from headsets, trackers or the climbing wall itself. With this, the platform presented lays the groundwork future exploration of novel feedback strategies, in ways not feasible with physical tools alone.

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17 https://github.com/felixkosmalla/unity-vive-reality-mapper

Part IV

CONCLUSION

9 GENERAL CONCLUSION

In this final chapter, we conclude this dissertation. We start with a summary of the works presented aiming at providing building blocks for future computer-supported assistive system. Then we frame and outline the combined contributions to the research questions posed in Chapter 2. Finally, we consider the limitations of our approach and describe potential future work.

9.1 SUMMARY AND CONTRIBUTION

To ground the artifacts and systems presented in this thesis, in Chapter 3 we built an understanding of the movement learning process and related work. In Section 3.1 we started with a presentation of different memory models and how motor memories are developed by considering various stage based models of skill acquisition. We noted that while the individual stages vary across the skill acquisition models, they can be aligned on a scale ranging from novice to expert. With a focus on the early stages of learning, we introduced different temporalities of feedback, identifying pre, during, and post performance as time points of interest for the artifacts of this thesis. Then, in Section 3.2, we gave an overview of feedback systems for movement learning while maintaining a center of attention to movements in sports but also touch aspects of rehabilitation. Here, we categorized systems based on their primary output modality such as auditory, tactile, and visual feedback. We found that assistive systems for sports show potential to improve movement guidance through feedback, however, their effectiveness depends heavily on the context and complexity of the targeted sport. While some feedback modalities and also the time of feedback shine in specific scenarios, this might not be the case in different contexts, especially when applying insights from simple tasks to complex skills [243]. With this, we highlighted the need for more research targeted at novel feedback methods tailored to underexplored dynamic and complex sports like rock climbing and slacklining. To do this, we further investigated the specifics of both rock climbing and slacklining in Section 3.3. This included looking at the origins of the sports, their motivational drivers and how these sports are practiced today by a broad audience. We ended each section with an overview on past Human Computer Interaction research in the context of both fields, opening up the floor for opportunities for assistive systems.

In the subsequent chapters, we presented the artifacts, tools, and systems with their accompanying studies. These can be aligned in a space that is spanned by the previously identified feedback dimensions *Time of Feedback* and *Information Bandwidth* (see Figure 9.1).

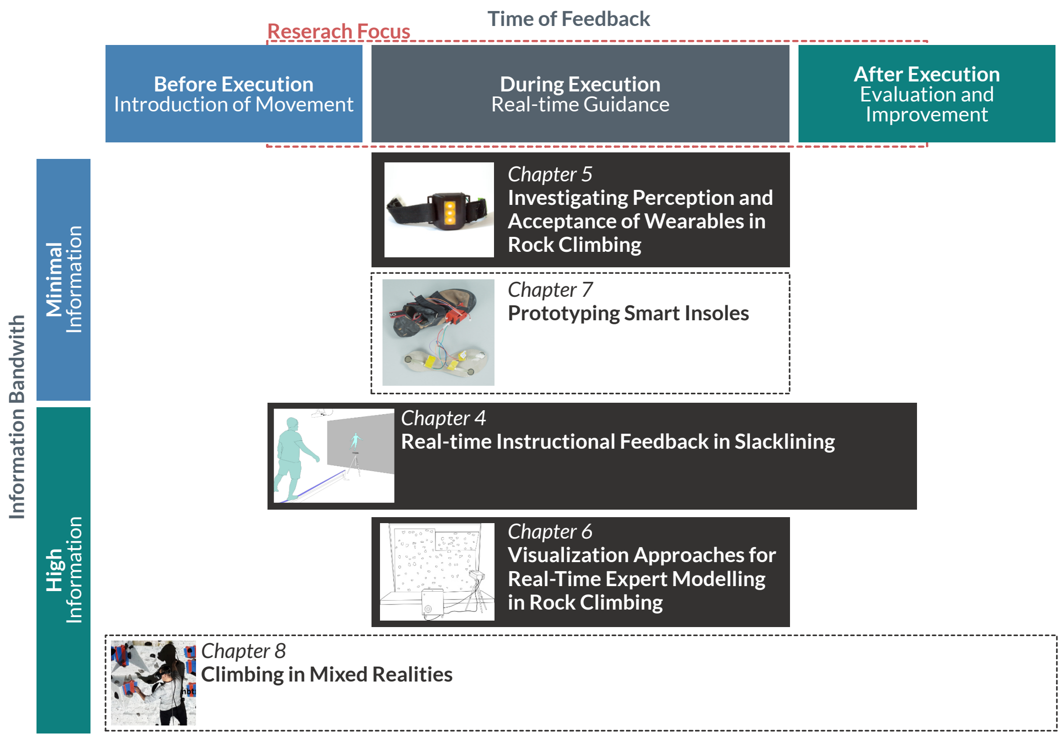

Figure 9.1: The artifacts presented in this thesis aligned in a space considering *Time of Feedback* and *Information Bandwidth* (see Section 3.2.6). Artifacts outlined with a dotted line represent technical contributions, while the others provide empirical insights.

In the following we will frame those artifacts and tools within this space, going from low information bandwidth to systems that convey feedback with a high information density.

Chapter 5 describes the investigation of feedback methods applied *during* rock climbing performances that can convey *low bandwidth* information such as a notification sent from the belayer, a cue in which direction to move next, or a simple, possibly automated reminder to pause and plan the next move. To do this, we implemented an online survey system that allowed participants to rate individual body parts in regard to the appropriateness to place a wearable device there. Additionally, participants could indicate the estimated perception of audio, visual, or tactile cues broadcasted from a wearable device during the climbing performance. The online study resulted in the design decision to implement a wrist-wearable-device to send out visual and tactile notifications in combination with head worn, bone-conducting headphones which were used to play audio cues. We conducted a study in a climbing gym to evaluate three feedback methods in a within-subject experiment. Consistent with related work, our results indicate that visual notifications delivered via the wrist are unsuitable as a real-time notification channel during climbing. This is evidenced by the slowest response times, the highest error rates, and the most missed notifications. In contrast, both audible and vibro-tactile feedback proved effective for delivering real-time notifications during climbing.

Chapter 7 complements the *Low Information Bandwidth* region with a toolkit for rapid prototyping of smart insoles that can assist *during* a performance. We demonstrated that with a minimal technical setup using readily available force sensitive sensors and a microcontroller a large variety of gait or foot pressure related events can be detected. An extended version of the toolkit was successfully used in a MobileHCI 2017 tutorial [42] on wearable computing in sports.

Going forward, we explored approaches to convey feedback with a *High Information Bandwidth*. In Chapter 4 we studied the design and implementation of an interactive slackline training assistant that guided participants through a set of training lessons derived from literature. The system was designed to give assistive, actionable feedback *during* the performance. Movements of the participants were captured with a Kinect v2, fed into the fully body gesture recognizer of the Kinect SDK to generate real-time guidance. Visual elements and textual cues were used to relay feedback with a *high information content*. *Before* the individual exercises participants were presented with both textual and video instructions. A performance review was presented to the participants *after* the performance giving an overview about the quality of movement and timing aspects. In a between-subject user-study, we compared learning basic slackline skills (e.g. walking on a slackline) using the system to the classical approach of a human trainer instructing the participants. Although both groups improved significantly before and after the training, we could not show a significant difference between the two approaches.

Continuing in Chapter 6, we investigated different visualization approaches for real-time expert modelling in rock climbing. For this, we employed different forms of augmented reality that used projections and augmented reality glasses to display both, an optimal movement and the trainees' performance, in the reference frame of a climbing wall, to the participant. The optimal movements in form of samples video recordings represent guidance with a *high information bandwidth* and showed the utilization of four distinct climbing techniques. A user study explored the advantages and disadvantages of each visualization in which we analyzed video recordings of pre- and post-recordings of the trials, complemented with semi-structured interviews. We found that none of the visualization techniques excelled in every aspect of guiding through a movement. Instead, we proposed a hybrid approach that combines multiple projection techniques that dynamically adapt the users current needs in real-time.

Chapter 8 explores rock climbing in mixed realities. We present the iterative development of a virtual reality rock climbing system that allows users to climb on a physical rock climbing wall by being immersed in a virtual environment through a head mounted display. With this platform, we envision multiple usage scenarios that are driven by research, training, or entertainment aspects. Using virtual reality allows for the decoupling of physical constraints from experimental design. This enables to investigate feedback systems that would not be easily feasible such as floating displays in space or trainer avatars that are perfectly aligned with the trainees body. Within this chapter, we present the evolution of a VR rock climbing system starting with climbing on a static wall with only a visualization of the climbers hands, to being able to climb on rock climbing treadmill with visualizations of both hands and feet. While no complete user study was conducted, informal trials have shown the feasibility and robustness of the system, leading to a seminar at Saarland University in which students had the opportunity to develop games using this platform. We concluded that chapter with possible future research directions of real-time feedback systems.

9.1.1 *Major Contributions to the Research Questions*

The research questions posed in Section 2.3 revolve around the foundational aspects of the conceptual idea of the Ultimate Assistive System. As mentioned in the beginning, it remains an open question how such a system will be achievable in the foreseeable future. However, by addressing these research questions, we aim to contribute to groundwork necessary for developing such a system. The answers to these research questions are not derived from a single study or chapter but rather from a combination of findings and experiences gained through the development and investigations of the former. Each chapter provides insights that, when considered together, form cohesive answers to the research questions posed. While the findings of the studies are explicitly valid for the sports of rock climbing and slacklining, generalized findings are formulated as answers to the research questions to inform the design of future systems and studies. In the following, we present those answers.

RQ 1: What are factors influencing the acceptance and willingness of athletes to use a computer-supported assistive system for sports training?

- Assistive systems should offer autonomy, reduce social pressure, and integrate seamlessly into training routines without disrupting movement.
  Chapter 4, Chapter 6
- Playful, engaging interfaces and structured, iterative learning approaches support motivation.
  Chapter 4
- Athlete preferences should be taken into account in regard to on-body device placement.
  Chapter 5

In an ideal world, a computer-supported assistive system would not be perceivable by an athlete, unless necessary. Perception happens, for example, when the system gives feedback using one or more modalities, such as vibration or an audio or visual cue. For wearable systems, this issue becomes even more pronounced. Depending on the form factor of the individual components of the system, devices can hinder the movement or be uncomfortable. With **RQ 1** we aimed to investigate factors that influence the acceptance and willingness of athletes to use an assistive system for sports training. During our studies, we found that participants appreciated the sense of autonomy that assistive systems entail (see Chapter 4). Using such a system could make the training schedule more independent, because, for example, no appointments with personal trainers need to be scheduled or met. Furthermore, these systems allow practicing on the users' own pace. In Chapter 4, participants also stated that playful, engaging interfaces that structure the individual lessons into manageable pieces of new movements could help them to stay motivated during a training schedule. Involving athletes early into the design process allowed to gain insights into sports specific characteristics, as seen in the online tool to assess the quality of body positions for wearable devices. Results showed that even positions that might initially seem impractical, such as near joints or other restrictive areas, could be tolerated if the perceived benefit of the device was strong enough. We used these insights to design output devices for rock climbing that balanced the devices' ability to convey feedback with being minimally obtrusive and safe to use (see Chapter 5). This goes in line with research promoting co-design in rock climbing [152, 153].

RQ 2: What are effective methods for tracking and assessing movements to inform real-time feedback development and testing in a sports context?

- Low-cost sensors and microcontrollers can support the rapid prototyping and iterative development of assistive systems for sports.
  Chapter 7
- Consumer-level tools provide adequate precision to study feedback methods through simplified movement tracking.
  Chapter 4

To contribute to future research we dedicated **RQ 2** to the question of to prototype software and hardware to gain insights into the effectiveness of in-situ feedback methods. While gold standards such as medical grade optical tracking systems such as Optitrack or Vicon result in an excellent representation of human movements, they require a high degree of instrumentation of both the environment and the participant, sometimes including cumbersome calibration procedures. This results in a more complicated study setup, longer preparation for the participants and even an influence to the perception of the participant in regard to the complexity of the assistive system. In this thesis, we show how the use of consumer grade soft- and hardware such as the Microsoft Kinect v2 can be used as viable input to generate in situ feedback for slackline training (see Chapter 4). Although we found situations in which tracking was not optimal, with a careful design of lessons, these restrictions could be circumvented. Further, in Chapter 7 we demonstrated how low-cost pressure sensitive sensors, readily available microcontrollers, and cardboard cutouts could be used to prototype smart insoles. The viability of this approach was shown by offering a tutorial in which participants were introduced how to set up such a system and implement simplified feedback based on gait. This approach reduces entry barriers for new researchers for conducting studies and allows gathering insights from real-world applications.

RQ 3: How could computer-supported assistive systems communicate feedback and instructions to athletes during training?

- Positioning feedback within the athlete's natural focus enhances real-time movement adjustments.
  Chapter 4, Chapter 6
- Mixed-Reality environments offer potential for flexible and controlled setups, enabling novel methods of feedback delivery and training.
  Chapter 8

RQ 3 investigated strategies for effectively communicating feedback and instructions to athletes during training, focusing on the integration of feedback into the natural flow of the activity. Across the different applications considered, we found that feedback should be delivered in ways that align with the athlete's focus and environmental constraints. The systems introduced in Chapter 4 and Chapter 6 presented the feedback in positions were the focus of the athlete naturally converges. In the slacklining system, a large projection was placed in front of the participants balancing on a slackline. The natural gaze during this activity is the front, thus visual feedback indicators, such as a simplified mirror-like representation of the user and instructional elements were laid out in an easily perceivable fashion. Similarly, projected video images were placed into the participants sight while mastering a climbing route. The projections were placed towards the natural gaze, adapted for each route to be climbed, allowing to stay focussed when grabbing the next handhold. A Google Glass, showing the participant form behind, overlaid with an optimal solution showed to be ineffective since the focal point of the eye had to be adjusted from the wall to the display of the glasses. Related to that, the wrist-based visual cues introduced in Chapter 5 during climbing posed a similar problem when the device was not in the sight of the participant, e.g. when looking down to adjust foot placement. Chapter 8 presents the implementation of a platform to realize mixed reality climbing experiences on physical rock climbing walls, both stationary and rotating. We argue that these technologies allow for the design of flexible, controlled environments where technology induced constraints or physical limitations in real-world setups can be mitigated. For example, drawbacks such as occlusion of lize-size projections during climbing (see Chapter 6) can be solved by *digitally* projecting directly onto the texture of a virtual wall or using 3D ghost avatars as seen in Section 3.2. Furthermore, different novel feedback elements such as floating displays, augmenting indicators or spatial audio could be investigated to eventually inform the design of real-world applications.

9.2 LIMITATIONS AND FUTURE WORK

The work discussed in this dissertation has certain limitations, offering potential areas for enhancement in future studies.

Limited Sample Size and Study Duration

A key limitation of the studies presented in this thesis are the restricted sample sizes, which may have masked significant differences in participant performance when comparing instructions of a human trainer and the assistive systems (see Chapters 4 & 6).

While we could show that in both cases the performance of the participants improved, future studies with larger participant groups might uncover significant differences in performance. This could provide insights into the relative effectiveness of human- versus system-instructed training.

Additionally, as discussed in the first part of this thesis (see Section 3.1.5), the systems and their evaluations focussed only on the early stages of learning, without investigating long-term retention. It is uncertain whether the findings made from the user studies conducted can be applied to later episodes of the learning progress. Although we compared participant's performances before and after trials when no augmented feedback was given (see Chapter 4 and Chapter 6), we did not conduct any longitudinal studies. In a literature review by Sigrist et al. [207], the authors give an extensive review about augmented feedback in motor learning, emphasizing that especially for complex tasks, concurrent visual feedback has predominantly been reported to be effective. This goes in line with our findings. However, Sigrist et al. summarize that the performance gain which is build up in the acquisition phase is lost in retention test. This is explained by the *guidance effect* [8] which states that continuous feedback during a learning task builds up a dependency on the feedback. Future research should investigate the long-term effects of the feedback methods proposed in this thesis while addressing the guidance effect. Countermeasures such as gradually reducing feedback intensity, as seen with faded feedback techniques [240], could help mitigate dependency on feedback.

Considering Intrapersonal Traits

The studies evaluating the assistive systems introduced in this thesis did not account for individual traits or characteristics of the participants.

Past research has shown that the ability to perform and learn new motor skills varies considerably between individuals [9]. Reasons for that might stem from different cognitive capabilities [119] or other physiological factors such as movement-to-movement variability [242]. Future studies could address this limitation and explore how integrating intrapersonal differences into assistive systems might enhance their effectiveness [58]. As a result, models could be developed to capture individual preferences, cognitive abilities, or motivational factors. Such models would then enable the design of personalized augmented feedback systems.

Considering Additional Input Modalities

The input modalities of the systems presented in this are limited to movement aspects of the participants, excluding other physiological factors.

In future work, these additional input modalities could include eye-tracking, or other psychological responses such as heart rate variability, galvanic skin response, or electromyography. Eye-tracking has been used in the past to detect uncertainty [26, 87], such as moments when an individual hesitates or struggles to decide on an action. A computer-supported assistive system would detect those moments and adapt the feedback accordingly, by e.g. in rock climbing prominently highlighting an area of interest such as a small foothold that otherwise might have been missed. Similarly, physiological signals such as blood pressure, heart rate variability or galvanic skin response could indicate stress or cognitive load [66, 168, 205]. Using this knowledge an assistive system might adjust the intensity of the feedback to avoid overwhelming the user. Furthermore, muscle activation patterns recorded via electromyography could be used to detect effort levels or fatigue [186]. Real-time feedback could prompt the users to reduce workout intensity or suggest another exercise that induces less stress on the body. Using these physiological indicators in combination with movement data could result in a feedback system that respond to the user's needs in a more holistic way.

Considering Additional Output Modalities

While in Chapter 4 and Chapter 6 we mostly focussed on visual feedback, in Chapter 5 we also investigated tactile and audio notifications in addition to visual cues. This limits the output modalities investigated in this thesis to visual, auditive and tactile feedback.

Future work could broaden the scope of output modalities, for example, by utilizing methods like electronic muscle stimulation, robotics, verbalized audio instructions, and mixed reality. Electronic muscle stimulation or robotics could be used to provide physical assistance (see Section 3.2.2), mimicking the interventions provided by a human. For example, a common guidance technique in climbing is to guide dynamic movements to demonstrate to the trainee how a movement should "feel". This could be used as inspiration for novel guidance techniques. Similar to the works of Ramsay and Chang [187], automatically generated verbalized instructions could guide athletes into the right movement or position.

Since hearing does not play a large role in rock climbing or slacklining, the use of this channel could be a suitable complement to the modalities explored in this thesis.

In Chapter 8, we proposed a virtual reality rock climbing system using a head mounted display. Here, we concluded with a series of future research directions that could leverage the visualization options offered by a VR system. With the current advancements of augmented reality headsets, findings of past research could be reevaluated on current hardware, integrating them into novel feedback methods. While VR can provide fully immersive training environments, AR offers the potential for context-aware, in-situ feedback overlaid directly onto the user's environment. This would ultimately enhance the realism of the feedback and possible resolve technical restrictions such as a narrow field of view as offered by current virtual reality headsets.

Expanding to Other Sports and Rehabilitation

The findings presented in this thesis are explicitly valid for the sports of rock climbing and slacklining. While addressing the research questions, we generalized some of these specific findings to make them applicable to future systems beyond the studied sports. However, further research is required to account for the unique characteristics of individual sports and movements. This includes the exploration of other sports as well as applications in the context of rehabilitation. In this area, computer-assistive systems could support patients in independently performing exercises and adhering to their training schedules, which remains a challenge [32] in current rehabilitation.

Integrating computer-assistive systems into rehabilitation programs could help reduce the burden on the healthcare system while complementing personal physical rehabilitation provided by physiotherapists.

Part V

APPENDIX

a

SLACKLINE SYSTEM

The following sections presents the questionnaires used in the study of the Slackline System as described in Chapter 4.

A.1 DEMOGRAPHIC QUESTIONNAIRE

Question 8 was only presented to participants training with the Slackline System.

1. Participant number: _____
2. Gender: Male _____ Female _____
3. Height: _____ cm
4. Age: _____ years old
5. Weight: _____ kg
6. How often have you tried slacklining?
   - Never
   - Sometimes (e.g., 1-2 times)
   - Intermediate (e.g., 3-10 times)
   - Advanced (e.g., over 10 times)
7. Last contact with slacklining:
   - Never
   - 1 month ago
   - 2-6 months ago
   - 6-12 months ago
   - Over a year ago
8. Experience with interactive devices (Kinect, Wii, PlayStation Move, etc.):
   - None
   - Beginner (e.g., tried 1-2 times)
   - Intermediate (e.g., played at a friend's house)
   - Advanced (e.g., owning such a device)

A.2 PHYSICAL ACTIVITY, EXERCISE AND SPORT QUESTIONNAIRE

We used a translated version of the Physical Activity, Exercise and Sport Questionnaire (Bewegungs- und Sportaktivität Fragebogen - BSA-F) by Fuchs et al. [72].

1/2

BSA-Questionnaire

Participant ☐

Q1 Are you employed, studying, or in an apprenticeship (also homemaker)?

☐ Yes (continue with Q2) ☐ No (continue with Q3)

Q2 Your job involves...

	None	Sometimes	Mostly	Always
sitting activities	☐	☐	☐	☐
some activities	☐	☐	☐	☐
intensive activities	☐	☐	☐	☐

Q3 On <u>how many days and how long</u> have you practiced the following activities in the <u>last 4 weeks</u>?

	on ... days	ca. ... min/day	None
Walking to work			☐
Walking to the supermarket			☐
Riding by bike to work			☐
Riding bike for other purposes			☐
Go for a walk			☐
Physically demanding homework (cleaning, tyding up, etc.)			☐
Physically demanding care work (maintaining kids or care recipient)			☐

Q4 On how many days and how long have you climbed stairs in the <u>last 4 weeks</u>?

on ☐ days ca ☐ floors/day None ☐

2/2

Participant ☐

Q5 Have you practiced sport activities in the <u>last 4 weeks</u>?

☐ Yes (continue with Q6) ☐ No (finished)

Q6 Which sport activities have you practiced?

A	B	C
☐	☐	☐
I have practiced activity **A** in the **last 4 weeks** for	I have practiced activity **B** in the **last 4 weeks** for	I have practiced activity **C** in the **last 4 weeks** for
☐ times	☐ times	☐ times
and each time for	and each time for	and each time for
☐ minutes	☐ minutes	☐ minutes

A.3 LATERAL PREFERENCE QUESTIONNAIRE

The lateral preference questionnaire was taken from [38]. Questions 14 was adapted to account for technological development while question 16 was updated for simplicity. Both questions concern the lateral preference of the ears.

14. **Original:** Into which ear would you place the earphone of a transistor radio?
    Updated: Onto which ear would you hold your phone if someone was calling?

16. **Original:** Imagine a small box resting on a table. This box contains a small clock. Which ear would you press against the box to find out if the clock was ticking?
    Updated: Which ear would you press against a box on a table with a small clock within, to find out if the clock is ticking?

A.4 GUIDING QUESTIONS OF THE SEMI-STRUCTURED INTERVIEW

The third block was only discussed with participants that used the Slackline System.

1. **General questions about the learning method**
   a) How was your general experience with this training method?
   b) What did you like the least?
   c) What did you like the most?
   d) Would you use this method and why?

2. **Application scenarios**
   a) Could you think of any other application scenario for exactly this training method with the slacklining approach?
   b) Could you think of any other sport activities, than slacklining, that could fit in this method?

3. **User Interface / System Feedback Evaluation**
   a) What did you like the most about the system?
   b) What was most frustrating / disturbed you?
   c) What would you change?
   d) How would you describe the system in one sentence?

b

INSOLE TOOLKIT

The following sections present the implementation details to the insole toolkit described in Chapter 7.

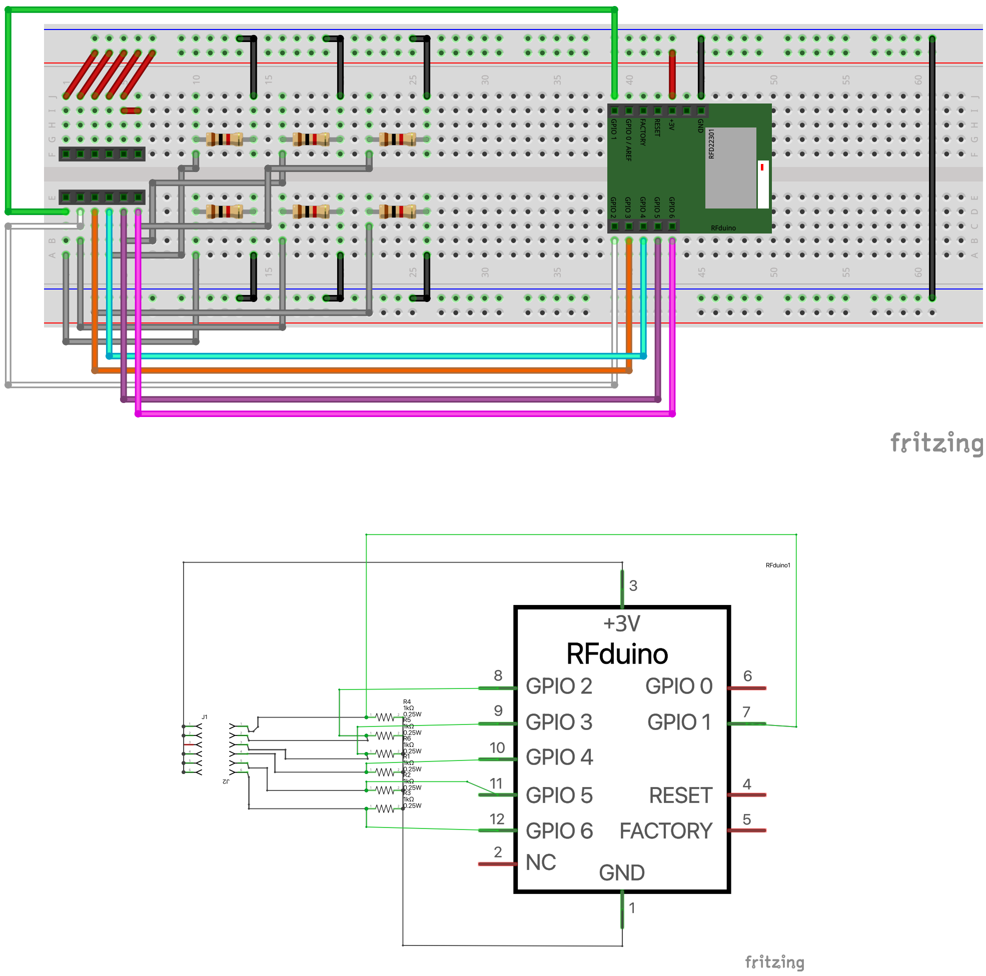

Figure b.1: Wiring (top) and schematic (bottom) of the ad-hoc smart insole

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