A thesis submitted to the University of Trento
for the degree of Doctor of Philosophy
in the Department of Information Engineering and Computer Science,
International Doctoral School in Information and Communication Technologies

Designing Wearables for Climbing:
Integrating the Practice and the Experience Perspectives of Outdoor Adventure Sports

Eleonora Mencarini
Cycle 29th

ADVISOR
Massimo Zancanaro, Fondazione Bruno Kessler (Italy)

CO-ADVISOR
Prof. **Antonella De Angeli**, University of Trento (Italy) & University of Lincoln (UK)

EXAMINERS
Dr. **Gabriela Avram**, University of Limerick (Ireland)
Dr. **Silvia Gabrielli**, Fondazione Bruno Kessler (Italy)
Prof. **Jonna Häkkilä**, University of Lapland (Finland)

Copyright statement

Statement of contribution

This disclaimer is to state that the research reported in this thesis is primarily the work of the author and was undertaken as part of her doctoral research. The work presented in Chapter 3-4-5 has already been published in the following papers:

- Mencarini, E., Leonardi, C., De Angeli, A., & Zancanaro, M. (2016, October). Design Opportunities for Wearable Devices in Learning to Climb. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*, p. 48. ACM.
- Mencarini, E., De Angeli, A., & Zancanaro, M. (2016, September). Emotions in climbing: a design opportunity for haptic communication. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, pp. 867-871. ACM.
- Fedosov, A., Mencarini, E., Woźniak, P., Knaving, K., & Langheinrich, M. (2016, September). Towards understanding digital sharing practices in outdoor sports. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, pp. 861-866. ACM.
- Wozniak, P. W., Fedosov, A., Mencarini, E., & Knaving, K. (2017, June). Soil, Rock, and Snow: On Designing for Information Sharing in Outdoor Sports. In *Proceedings of the 2017 Conference on Designing Interactive Systems*, pp. 611-623. ACM.

The content of these papers has been partially re-interpreted and rewritten and partially quoted verbatim.

The wearable prototype presented in Chapter 5 was developed in collaboration with other researchers. In the chapter, their contribution is clearly stated. It consisted in manufacturing and assembling the hardware and in developing the software. The rest of the research work was conducted by the author. The author covered several roles for which she will be referred to as:

- **Researcher** who defined the research problem and plan, recruited the participants (climbers, designers, mountain guides), contacted the climbing gym, elaborated the materials that guided the activities, and conducted the data analysis.
- **Observer** during the fieldwork (conducting also the interviews) and the prototype evaluation.

- **Facilitator** during the activities performed by the participants such as the workshops and the evaluation. This role shows the different attitude that the researcher has held during the research process, adjusting the level of prominence of her presence and participation of potential users according to the different phases of the research process.
- **Designer and Craftsperson** of the interactive prototype.

Abstract

This thesis positions itself within the stream of research on HCI for sport and addresses the topic of designing wearable devices for sport. To date, the design of wearables for sport has focused on the measurable aspects of performance such as speed, heartbeat and calories burnt. Such design is driven by the possibilities offered by the miniaturisation of components and the trend to have a healthy lifestyle. The conjunction of these two trends, has created a breeding ground for technologies that offer self-tracking to improve personal fitness, health and wellbeing. Although these kinds of devices have great success on the market, several studies have shown poor long-term adoption, with people generally ceasing to use their devices around six months from the time of purchase. This thesis argues that the wearables produced until now do not address the full range of needs that sportspeople have and so aims to design wearables on the basis of a thorough understanding of the sport practice.

The leading research question in this work was: *what are the elements to consider for the design of useful, acceptable and desirable wearable devices for sport*? This broad research question was then operationalised in two sub-questions: *what elements constitute the sport practice*?; and *how can wearable devices support such practice*? By adopting a practice perspective and a subsequent research methodology based on situatedness, embodiment, and co-design, it was possible to identify aspects of sport other than performance. Emotions, trust and community values emerged as pivotal aspects of the climbing experience. These findings led to the design of wearables for augmenting the interpersonal communication of the actors involved. This introduces a new role for wearables supporting sportspeople, which as a facilitator of expertise rather than a tracker of activity.

The main contribution of this thesis is the articulation of a conceptual framework for the design of wearables for outdoor sports, with the goal of better acceptance and long-term adoption. The conceptual framework outlined here breaks down the complexity of the sport practice by identifying the elements that define it (i.e. type of performance, emotional involvement, social dynamics, physical context, values) and articulating their orchestration with product design aspects (such as ergonomics, comfort, and perceptibility) and the cultural value of wearing an artefact on the body.

Acknowledgements

The risk I took was calculated, but man... am I bad at Math!

I thank my advisors Massimo Zancanaro and Antonella De Angeli for guiding and teaching me so much in the last four years. I would like to thank also Luigina Ciolfi, Daniela Petrelli, and Nick Dulake from the Sheffield Hallam University for being so inspirational and allowing me to look at my work with fresh eyes.

I am grateful to my i3 colleagues, who have always supported me. I would like to thank especially Chiara, who has always answered to my doubts lightening up the dark tunnel of research and has always stimulated my thoughts. Alex for the trust he has always had in me. Gianluca for his inspirational solidity, and Michela for sharing beautiful and bad moments in the office. And of course, also Paolo, Elena, Nadia, Ornella, Andrea, Carolina.

This thesis has been possible thanks to the curiosity and free engagement of people who decided to invest their valuable time and effort to help me. I am extremely thankful to them. Therefore, I would like to thank Davide Giovanelli from E3DA-FBK and Charles Callaway for their technical support, Ermanna Marchetti and the Unisport Office of the University of Trento, Andrea Zanella, the alpine guides and all the beginner climbers I met for their helpfulness.

On a personal side, I thank my 'sparring partners' for climbing Alessandro F. and Guido, for their patience with my difficulties in climbing and for having brought me to climb as much as possible. I thank Alessia for being such a genuine person and having shared beautiful moments at the beginning of this period in Trento. Elia with deep gratitude for making me realise that doing research means to have the "courage to try" and for having taken pictures of all the pages of the MacAloon and Csizenmyhali book that he found in NY. Roberto for having always tried to show me the positive side of doing a PhD. Elena V., a kind friend. Irena, a certainty. Andrea and Carlotta for being breath of home in Trento. Linda for the anthropological view of this period of life, which created the necessary detachment to make fun of it. Ailbhe and Sinan for being friends around the world. Elena and Filippo because when you grow with people they become your home and you bring them with you wherever you are.

Finally, I thank my parents, my sister, Enrico and Pietro for supporting me, even at a distance. And I thank Giulio, for having supported me in the last moments of this educational adventure.

TABLE OF CONTENT

01 Introduction

1. Introduction

This thesis builds on the acknowledgement of poor levels of adoption of wearable devices by sportspeople. This evidence has paved the way for an investigation of what is typically offered by the wearable devices for sport currently produced on the market and in research, what elements constitute the sport practice, and how these elements may benefit from the support of a wearable device.

This introductory chapter presents the motivations for this work, introduces the research questions and contributions of the thesis, explains the methodology adopted and the case study chosen, and outlines the structure of the thesis.

1.1 Problem Definition

In the last 15 years, HCI has largely contributed to the topic of wellbeing, i.e. the promotion of a healthier and more active lifestyle, especially by proposing technologies that motivate people to practise physical activity. This persuasive goal was pursued through different motivational techniques, such as Personal Informatics (or Quantified Self,) i.e. awareness of one's own performance and physical conditions through data visualisation (Consolvo et al., 2008; Pavel, Callaghan, & Dey, 2012); gamification (Zhao, Etemad, & Arya, 2016) or the sharing of personal information with others (Ahtinen et al., 2009) thus enacting peer pressure (Consolvo, Everitt, Smith, & Landay, 2006) or playfulness (Ahtinen, Huuskonen, & Häkkilä, 2010).

In order to reach a large portion of the population and to accompany them in the leisure activities of their life, the technology used for promoting healthy lifestyles had to be pervasive, ubiquitous, and personal at the same time. At the beginning, the most common technologies for monitoring and fostering physical activity were mobile devices and smartphones, while in the last five years wearable devices have gained a greater popularity both in research and on the market since they radicalise the concept of portable technology and use in mobility. Being worn directly on the body, the main fields of application for wearables inevitably relate to health and wellbeing, including sports. The wearables for sport currently on the market are also known as activity trackers since they are equipped with sensors able to measure certain aspects of body performance such as distance travelled, steps walked, heartbeat, calories consumed, and hours slept, allowing users to monitor their physical status during their various daily activities. The attractiveness of these devices is so high that nowadays many different companies are present on the market with their own wearables. Indeed, besides the specialised companies such as Fitbit and Jawbone, generic sport brands such as Nike and geo-location brands such as Garmin also produce and commercialise their own activity trackers.

Despite the growing interest of people in activity trackers, market and research studies have demonstrated that there is a high rate of dropout shortly after purchase (Canhoto & Arp, 2017; Ledger & McCaffrey, 2014; Shih, Han, Poole, Rosson, & Carroll, 2015). According to a study by Endeavours and Partners (Ledger & McCaffrey, 2014), a third of buyers stop using their devices within six months of the purchase. The reasons for this rapid disenchantment are twofold. Some explanations have been found in technical shortcomings, such as the limited accuracy of the data collected, too few functionalities, and in the fact of not being stand-alone products, but instead requiring integration with smartphones (Ericsson Consumerlab, 2016). Other reasons can be attributed to producers' lack of appropriate understanding of sportspeople's needs and practices.

From the users' perspective, the benefits of using activity trackers are not always clear, advocating for a better user experience design. For example, Rapp & Cena (2015) found that new users perceived the task of collecting data as burdensome, and Karapanos et al. (2016) found that the numbers used in data visualisation are often meaningless to users. Another reason for dropout relates to the devices' influence on owners' identities. Lazar et al. (2015) showed that people stopped using wearables also because they felt the devices did not conform with the image of the ideal sportsperson that was advertised by the wearable's brand. Similarly, Gouveia et al. (2014) reported that the failure to adapt to standardised goals led many users to experience feelings of underachievement and incompetence. Also, there are categories of sportspeople, such as wheelchair users, who may not accord with the standardised and highly performative user profiles target by the wearables currently available on the market, hence feeling excluded (Carrington, Chang, Mentis, & Hurst, 2015). The problem of standardisation also underscores the need for contextual design for such technologies. For example, Patel and O'Kane (2015) demonstrated that using activity trackers in gyms can be difficult because activities, context, and personal attitudes are discontinuous. Also, Shih et al. (2015) found that the design of wearable devices should consider the real needs and expectations of users such as the need for a reminder to wear the device rather than reminders for the activity goals, or the gender differences in lifestyle. Accordingly, Nurkka (2016) found that customisation is an important feature for owners of wearable devices: it influences purchase choice, it is used to adapt features (rather than for fun or aesthetics) and the adaptation is a continuous process not limited to the first changes made straight after purchase.

On the basis of the studies reported in this section, this thesis acknowledges a prevailing narrow view on wearables for physical activity, which mostly focuses on performance and offers a user experience that is too standardised, and a too wide view on sports, which are often reduced to generic physical activity. Conversely, this thesis focuses on sports intended as a "*physical activity that is planned, structured, and repetitive and as a final or intermediate objective the improvement or maintenance of physical fitness*" (Caspersen, Powell, & Christenson, 1985) and excludes general physical activity intended as "*any bodily movement produced by skeletal muscles that results in energy expenditure*" (Caspersen et al., 1985) that happens as side effect of other tasks, e.g. going to work. This argues that sports are much more complex practices than what activity trackers can capture and return, and that current wearable devices for sport do not address the full range of sportspeople's needs. This thesis therefore adopts a different approach to the design of sport wearables, which aims to benefit users not by motivating them to practice sport, but by offering new and meaningful social experiences, enhanced self-esteem, and respect for their ideal self (Karapanos et al., 2016) while practicing it.

1.2 Research Questions and Thesis Contribution

To date, the majority of HCI studies in the domain of sports have focused on prototyping wearable devices to support sportspeople's performance during training (Bächlin, Förster, & Tröster, 2009; Cauchard, Cheng, Pietrzak, & Landay, 2016; Ladha, Hammerla, Olivier, & Plötz, 2013; Stewart, Traitor, & Hanson, 2014) or during the learning phase (Hasegawa, Ishijima, Kato, Mitake, & Sato, 2012; Schmid, Kleemann, Merritt, & Selker, 2015; Spelmezan, 2012). Other studies have addressed the social aspects of sport by building and testing devices that enrich team awareness (Mauriello, Gubbels, & Froehlich, 2014; Page & Vande Moere, 2007; Walmink, Wilde, & Müller, 2014) or audience cheering (Curmi, Ferrario, & Whittle, 2017; Tomitsch, Aigner, & Grechenig, 2007; Woźniak, Knaving, Björk, & Fjeld, 2015). Finally, other work has focused on the enhancement of the sport experience itself (Colley & Häkkilä, 2017). So far, HCI research has paid little attention to the emotional and cultural aspects of sports, despite their relevance being highlighted in the literature of sport psychology (Hanin, 2007; Vallerand & Blanchard, 2000) and sociology for sport (Lewis, 2000). Moreover, there is a lack of systematic knowledge on the various elements that compose the sport practice and on how they can influence the design of wearables for sport.

This thesis adopts a different starting point: a user-centred approach that grounds the design in a deep investigation of the sport practice to chart unexplored design spaces and user needs which wearables could address. In line with this approach, the research question leading the work was:

RQ: *What are the elements to consider for the design of useful, acceptable, and desirable wearable devices for sport?*

This question was addressed through the case study of sport climbing, selected because it is a multi-faceted sport that entails both an individual and a collaborative dimension, and both physical and mental effort. The research question was then broken down into two sub-questions to address the specific case study:

RQ1: *What elements constitute the practice of climbing*?

RQ2: *How can wearable devices support such practice*?

This thesis aims to reduce this knowledge gap in the domain of HCI and Sports with a threefold contribution:

1. A methodological contribution, which applies to sports in general. This methodological contribution consists in framing sports as socially shared and culturally defined practices as well as personal experiences composed of physical, sensorial and emotional involvement. The methodology adopted in this thesis was based on a Practice Paradigm perspective and on the principles of situatedness, embodiment and co-design. This methodology was adapted to the domain of sports, where situatedness and embodiment have been orchestrated with co-design in order to ensure an understanding of the sensorial involvement and tacit knowledge of sport to both the researcher and the participants, thus fostering an empathic design solution. Furthermore, following this methodology the wearable technology produced has been left to acquire meaning by placing it within the practice of the sport.

2. A conceptual framework that articulates the design of wearables for outdoor adventure sports, in order for them to be meaningful to the potential users, and thus pave the way for a better acceptance and long-term adoption. This framework is the result of the comparison between what emerged from the research and design process on climbing and the literature on outdoor sports and on the design of wearable devices. It breaks down the complex character of the outdoor sports practice by identifying the elements that compose it and showing how these elements inform the specific product design requirements of a technology meant to

be applied to the body, such as wearables. The elements identified include the sport culture, activity, the physical, cognitive and emotional involvement of the sportsperson as well as the aspects of the wearable device both as a technological and aesthetic artefact. This holistic vision, which includes elements of the sport practice other than performance, has not previously been considered in HCI.

3. A kit of vibrotactile wearable devices for augmenting interpersonal communication in rock climbing, which is the result of the identification of a design space that includes elements of the sport practice other than performance. In particular, this thesis expands the design space of wearables for climbing to the emotions and values involved in the sport practice and opens up to new roles beyond that of activity tracking. In the case study analysed in this thesis, this new role has been identified in supporting the relational aspect of learning by enhancing interpersonal communication between sport participants.

1.3 Theoretical Foundations

Human-Computer Interaction (HCI) is a fairly recent discipline, dating back to the 1980s. In the last 30 years, HCI has evolved together with the diffusion of technology through all areas of society. In the early 1980s, computers were used mostly in the workplace and their purpose was to facilitate and support workers to accomplish tasks and manage large quantities of data. The 1990s saw the diffusion of the PC - computers entered people's houses and began to serve leisure purposes as well as work. Later on, the evolution of technology led first to mobile devices which pervaded all the contexts of people's lives and then to wearable devices which, besides accompanying the user in every context, continuously stream data. The evolution of HCI research topics and methods runs in parallel to the evolution of this technology. This evolutionary process does not discard the first research interests in the discipline but adds new ones to the corpus.

The evolution of HCI research can be classified in three waves (Bødker, 2006) or paradigms (S. Harrison, Tatar, & Sengers, 2007). The first wave is characterised by the drive for optimisation of work processes. Here, the main research interest was the reduction of possible human errors (human factors) in the interaction which may cause critical incidents, by identifying usability guidelines for the interface. The research methods were borrowed from the scientific disciplines of engineering, ergonomics, and cognitive sciences, and the main outcomes where rigid guidelines and formal methods. The second wave is characterised by a shift in the conception of users "from human factors to human actors", to borrow the title of Bannon's (Bannon, 1992) paper, and the opening up of the analysis of the human-computer interaction towards the aspects of context and sociality. People use technology as artefacts to reach goals and they are not isolated when using it; rather, they are collocated in a context and collaborate with others. The main methodological approaches involved in this wave are Contextual Design, Activity Theory, Distributed Cognition, and Participatory Design. The third wave is characterised by the investigations of how people use computers both in the public and private spheres of their lives. Such investigations extend to the purposeless interactions that acquire meaning from the context where they occur. Therefore, HCI research interests have widened to the investigation of culture, emotions, and user experiences. The methodologies used in this wave takes advantage of creative, proactive methods such as Cultural Probes.

Recently, Kuutti and Bannon (2014) have identified two main theoretical approaches within HCI, which cut across to the three waves: the Interaction Paradigm and the Practice Paradigm. These two paradigms differ in their focus of research and methodology adopted. While the Interaction Paradigm focuses on the dyadic relationship between user and machine and treats this interaction as momentary and ahistorical, the Practice Paradigm puts human practices at the centre of attention, with technology intended to support these practices. The authors define practices as relatively stable actions, continuously produced and reproduced, situated in time and place, and thus dependent on the material and cultural features of the environment, and historically determined. The context of interaction is considered by both paradigms, but its relevance is different. In the Interaction Paradigm, context is one of the many aspects that affects the interaction and can be treated separately from it. In the Practice Paradigm, the interaction between person and machine acquires meaning only if situated in the context. In this case, the context is at the same time physical, with its materiality and the required embodiment, and social, with the multiplicity of actors involved, and cultural, with the values that help interpret the world and give meaning to the actions.

Unlike the Interaction Paradigm, which is characterised by an experimental methodological approach, the Practice Paradigm takes a phenomenological stance:

> *"Because practices are contingent, mediated and cannot be understood without reference to the particular place, time and concrete historical context where they occur, they can only be studied 'close-up'. (...) they must be studied where occur, in their natural setting. Research methods have often been qualitative, in situ, observational studies, extended over time, studying*

> *an overall activity, involving people, artefacts, organisational routines in daily practices"* (Kuutti & Bannon, 2014).

As affirmed in the two previous sections, this thesis posits the original assumption that sports are a multifaceted and complex practice that consists of cultural and social aspects, such as values, as well as personal and experiential aspects, such as emotions and sensorial perceptions. Therefore, this thesis tries to answer to the research questions by assuming a practice paradigm perspective and joining the research themes typical of the third wave investigating the sensorial and emotional aspects of the sport experience.

1.4 Methodology

This thesis has applied the principles of the Practice Paradigm by adopting a research methodology based on embodiment and situatedness (Tomico & Wilde, 2016; Dourish, 2004), and co-design (Sanders & Stappers, 2008; Vines, Clarke, & Wright, 2013). To get a holistic understanding of the sport practice, the investigation included the sensorial, the personal/intimate, and the collective dimensions of sport. The sensorial dimension of sport was investigated through field observations analysed according to models of Contextual Design (Beyer & Holtzblatt, 2009), which aimed to map the materiality of the artefacts used and the physical settings, the flows of communication, the sequence of actions, and the values embedded in the practice. The personal and intimate dimension of sport was investigated through individual semi-structured interviews to get insights into motivations, goals, difficulties, and emotions. Great relevance has been given to emotions, which were investigated through dedicated methods (i.e. Russell, 1980) with the aim of connecting them with the other aspects of the practice. The collective and cultural aspects of the sport have been investigated through focus groups to gain insights into the values shared by the sport community, which, if included in the design, might influence positively the acceptance of technology (Friedman, 1996).

In the design phase, embodied and situated creative methods have been orchestrated with a co-design approach in order to elicit more empathic responses from the participants. Co-design is an approach based on the involvement of potential users in the design process with the purpose of helping, on the one hand, designers to gain insights from participants' knowledge and, on the other hand, participants reflect on their current practices, thus fostering empowerment towards a possible change and making the design process more democratic (Vines et al., 2013). In the context of this thesis, climbers and designers were invited during the co-design workshops to explore the possible solutions that wearable technology could provide to climbers' needs. Climbers were invited to participate because they are experts in their sport and their expertise was crucial to steer the design towards a useful, acceptable, and desirable technology, while designers were invited because of their expertise in the creative process. The choice to adopt a co-design approach required mutual learning (Simonsen & Robertson, 2012) by both types of participants, to set a common ground to work together. To enact this mutual learning, contextual bodystorming was adopted during the final workshop as a creative method to leverage on the inspirational power of the context and the activity. Bodystorming - in the double meaning of experiential understanding of the context and the activity and of acting out envisioning scenarios (Schleicher, Jones, & Kachur, 2010) – allows participants to step into users' shoes and experience users' sensations first-hand, which can be revealing. Putting designers in climbers' shoes had the aim of generating a more empathic design, which emerges when designers are able to grasp what is involved in the felt experience of user's lives and what is like to be in a situation from their perspective (Wright & McCarthy, 2008).

Finally, the evaluation was conducted 'in the wild' (Rogers, 2011), i.e. during a climbing lesson in a climbing gym, to ensure that the new artefact produced would integrate with the authentic practices of the sport community, and to foster participatory sense-making and appropriation by potential users (Kuutti & Bannon, 2014).

The context of the practice has been considered along all the research process in order to ensure the gathering of insights which are rooted in the embodiment and situatedness of the activity. Nevertheless, for the sake of clarity, it is necessary to specify that the studies presented in this thesis (the observations, the co-design workshops and the evaluation) were conducted indoors. This is due because climbing is an outdoor sport born from alpinism, which nowadays can be practised indoors as well (as it will be thoroughly explained in "The case study" section). Actually, nowadays it is much more common to have the first approach to the sport in climbing gyms (at least in the geographical are where the studies were conducted) and then, once the basic skills are acquired, to move to outdoor crags. For the purpose of this thesis, indoors gyms were preferred as the setting of the studies for a matter of practicality: they can be booked, are easier to reach, and offer wider spaces where to organise activities. Nevertheless, the outdoor dimension of the sport has been actively investigated and kept into consideration throughout the research process of this thesis.

1.5 The Research Process

The research process consisted of three phases and seven research activities (see Figure 1). The three phases are the typical steps of a HCI process, i.e. Understanding, Designing and Evaluating (Preece, Rogers, & Sharp, 2015). The Understanding phase sought to gain a thorough knowledge of the climbing practice and included a fieldwork which investigated beginners' difficulties and instructors' strategies through observations and interviews, and climbers' attitude towards wearable technology via focus groups. From these initial studies, it emerged that emotions play an important role in learning to climb, and that the values shared by climbers strongly affect the likelihood of their acceptance of technology. Beginners described climbing as an alternation of fear and relief that can be overcome if there is a trusted partner and thanks to the instructor's suggestions; while experienced climbers are motivated by the values of self-efficacy, pride, and a sense of adventure, and would accept a technology that positions itself as a support for their expertise rather than as a substitute for it.

These results were the basis for the Design phase which started with a co-design workshop aiming to explore the potentialities of wearable devices to meet climbers' needs while also respecting their values. The outcome of this workshop was a series of concepts focused on raising the awareness of the involved actors on the invisible phenomena of climbing, such as climbers' balance and the attentive presence of the person 'on the ground' (i.e. partner or instructor) and enabling communication between partners at a distance. Moreover, because climbers might be tense while climbing, it emerged that a subtle form of communication was needed in order not to overload them cognitively and haptic feedback was found to be the best modality for this purpose. Afterwards, the design phase proceeded by exploring the available technology for haptic feedback.

Vibration was selected as the best option for its modulation ability and low energy consumption. A second co-design workshop was then held to explore the use of vibration for augmenting interpersonal communication in climbing. This workshop was conducted in a climbing gym where brainstorming techniques were combined with physical engagement to help participants achieve a more empathic understanding of climbing dynamics. Insights were gained into the possible configurations that vibrotactile motors can assume to convey different meanings, suggesting different possible shapes of wearables.

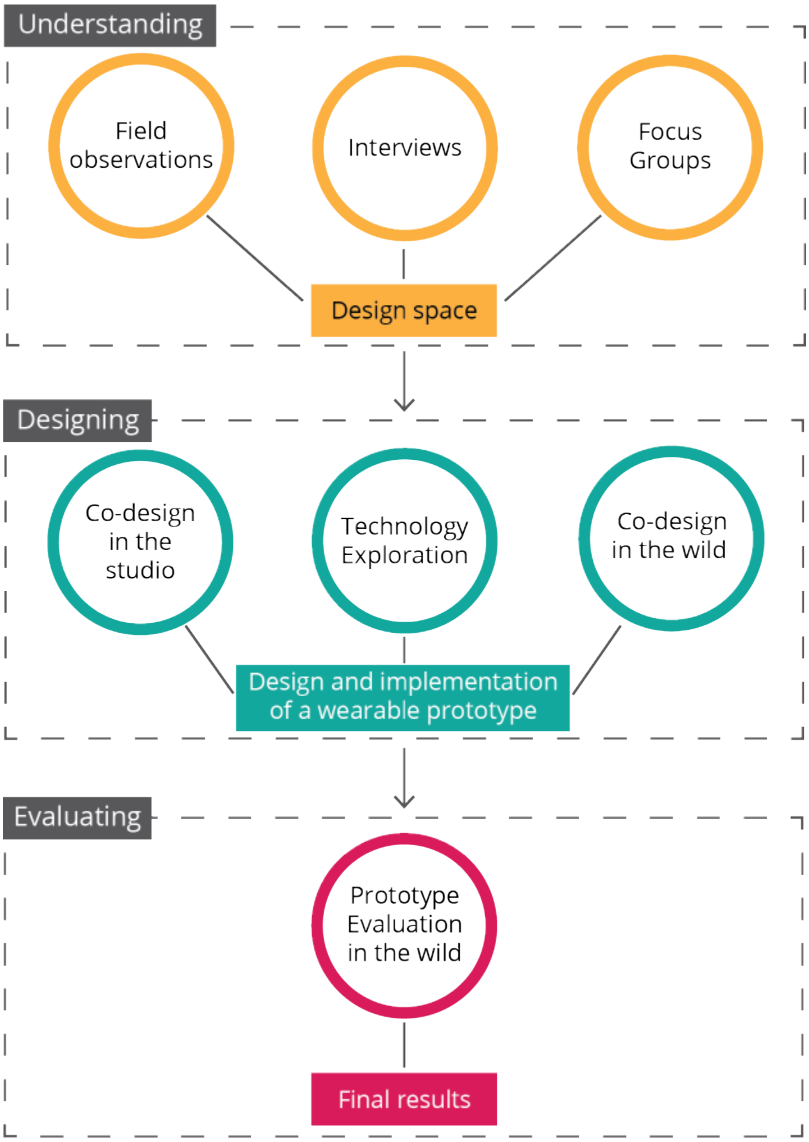


Figure 1. Scheme of the research process.

These concepts were finalised into a wearable prototype for augmenting the communication between instructor and beginner climbers through vibration. The system was composed of eight devices – controlled from a tablet interface - to wear on the parts of the body involved in climbing movements. This system was designed to enable the instructor to support the beginner in the learning of correct movement techniques while s/he was on the wall. Finally, the prototype was evaluated by a mountain guide and beginner climbers 'in the wild', i.e. during a lesson in a climbing gym. During the evaluation, this set of wearables was considered as a probe because it was used to address unresolved issues, such as the perceived usefulness of the devices, which location(s) on the body, and level of pleasantness/annoyance of the vibration. From the evaluation, it emerged that the vibration, despite causing surprise when it was received, helped climbers feel reassured because they sensed they were being watched. Regarding the perceived usefulness, both the trainees and the guide found it helpful to provide a nudge on a specific body part in real time and they appreciated the possibility of customising the purpose of the message, i.e. as a feedback or an instruction. These findings, together with climbers' preference to wear the devices on the ends of the limbs and on the abdomen, pave the way for the design of a kit of auxiliary wearables to adopt when needed and adjust to the purpose of the moment.

1.6 The Case Study

Sport climbing was selected as the case study of this thesis for its richness and complexity in addition to a personal interest of the author. It entails both an individual and a collaborative dimension: the climber is alone on the rock but has a partner on the ground, the belayer, who takes care of her/his safety by handling the rope through a friction device in order to halt a possible fall of the climber. Therefore, the two need to coordinate their actions during the ascent in order to manage the rope. Sport climbing requires simultaneous physical, cognitive, and emotional effort to perform well. Moreover, it can be practised indoors as well as outdoors – the latter entailing a close connection with the environment.

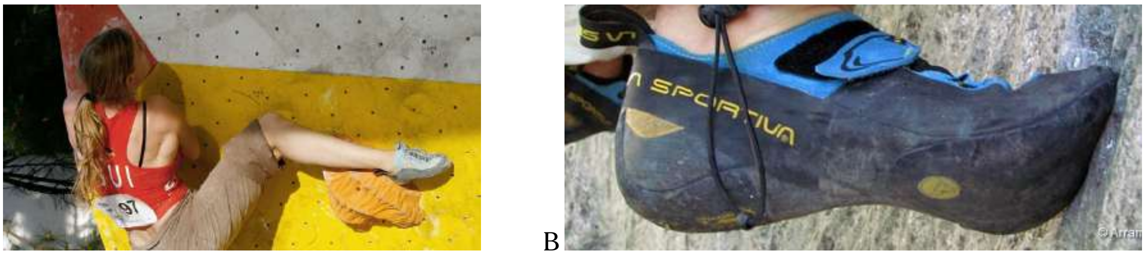
Climbing evolved from alpinism and nowadays it includes many sub-disciplines, e.g. ice climbing, sport climbing, bouldering, solo, trad, etc. This thesis focuses on *sport climbing*, although many references to alpinism will be made when reporting opinions from experienced climbers. Sport climbing differs from trad climbing and alpinism because it "*relies on permanent anchors fixed to the rock for protection. This is in contrast to traditional climbing where climbers must place removable protection as they climb*[1]". For a definition of the other most common types of climbing see the Glossary in the Appendix.

The climbing performance is characterised by balance and effective movements, rather than speed. The movements involved in this sport require a skilful use of the body to find the most efficient way to move up the wall without wasting physical and mental energy. Notably, in climbing the body is used like an artefact since it is the only tool climbers have to tackle the wall. The equipment they use is meant to ensure safety; the only artefact meant to support the performance are the climbing shoes. Two examples of climbing movements that require a skilful use of the body are the 'heel hook' where the climber uses her/his heel to anchor and push her/himself up, or the 'smearing', which consists in pressing the soles of the climbing

[1] https://en.wikipedia.org/wiki/Sport_climbing

shoes on the rock and using friction to gain vertical ground. For a visual representation of these techniques, see Figure 2. Moreover, because climbing involves an unmediated relationship with the wall, the sense of touch is fundamental and always on the alert. By tackling the wall with bare hands, climbers feel the materiality of the rock as they search for the best holds, and through the spatial sensations of touch, like kinesthesis and proprioception, they perceive the inclination of the wall and adjust their balance accordingly (Dutkiewicz, 2014).

A



B

Figure 2. A) Heel hook; B) Smearing

Since the 1980s, the vertical dimension of the sport is reproduced in gyms through high walls equipped with plastic holds, different inclinations and volumes that allow reproducing some characteristics of the rock walls, such as roofs or crags. In indoor gyms the outdoor conditions are simplified; what is maintained is the core element of the verticality so that climbers can experience the motor patterns required to maintain balance while move along a vertical wall, the fear of height, the management of the rope, and the coordination with the belayer in situations of distance and noise. What is lost is the time spent approaching the rock wall and the consequent feelings of immersion in nature and exploration, the need to interpret the environment considering the different types of rock and the weather conditions, the sensorial richness (e.g. (the temperature of the rock, the view, the wind) and the need for 'reading the rock', i.e. to find the proper holds, which in nature are holes in the rock, whereas on artificial walls, the path to follow is signalled by protruding and colourful holds.

Although climbing is becoming more and more popular thanks to the increasing number of indoor gyms and improved safety (Gardner, 2015), it is still considered an extreme sport. The evolution of this sport from alpinism to indoor practice has made it accessible to all, but the emotional involvement it entails has remained. By its nature, sport climbing involves high levels of adrenaline and requires high level of awareness and focus. Know-how and precise movements are fundamental for safety and to conserve as much physical and mental energy as possible.

1.6.1 The Climbing Experience

The experience of climbing and the motivations behind the choice to practise this sport have been partly investigated in sport psychology, sport sociology, and HCI. MacAloon et al. (1983) describe climbing as one of the sports that entails the highest levels of flow. With the term 'flow', the authors describe those moments when somebody is completely focused and in control of what she is doing, with no external thought or emotion to interfere, and finding pleasure in the activity itself, regardless of the results. Being in a state of flow is not an objective condition, but it depends on the subjective perception of the challenges that an activity provides; there has to be a perceived challenges-skills balance. Climbing can be a great source of flow because there are several levels of difficulty, among which every climber can choose the challenge that better matches her skills, and it requires a deep focus, which makes the climbers totally absorbed in the activity and isolated from the rest. In his progressive model of the motivations for climbing, Levenhagen (2010) puts flow at the initial stage, followed by the building of character and the realisation of a greater spiritual self. The 'building of character' consists in the demonstration to the self and to others of the climber's value by engaging in more and more difficult climbs, while the 'realisation of a greater spiritual self' refers to the creation of a meaningful world and the desire to deliberately tame it, at a risk to her/his life. Across the literature, Byrne & Müller (2014) identified five motivational themes for sustaining climbers' engagement in the sport. They are i) *maintaining challenge* since challenges are useful to find flow and achievement, and climbers can build their character through achievement; ii) *risk as a measure of progress* meaning that although risk in itself is not a real motivation for climbing, by climbing risky routes climbers realise their improvements; iii) *social engagement* as a source of intrinsic and extrinsic motivation through competitiveness and acknowledgements; iv) *documenting and reliving the experience*; v) *experiencing beauty and nature*. Focusing on the sensorial aspects involved in the climbing experience of beauty and nature, Lewis (2000) underlines the unmediated relationship with the rock through the physical and tactile engagement, and the achievement of a sense of freedom that comes from the sense of human embodied agency on the environment.

1.6.2 The Author's Climbing Experience

I started to practise sport climbing one year before starting the PhD. I attended two courses organised by the Sport Association of the University of Trento: a beginner course in February 2013 and an intermediate course in November 2013. I chose to start practising climbing because it is a very common sport in the city where I moved, i.e. Trento. The stories from the weekend adventures told on Monday mornings by my colleagues at work, the language full of technical terms, the knowledge of the environment, the long discussions about the gear and the brands, fascinated me. Somehow in Trentino climbing means being part of the local community. Then, when I started my PhD, I decided to develop my personal research interest on embodied interaction, qualitative user studies, and design and I deemed climbing to be an appropriate case study for that purpose. It would have allowed me to analyse the involvement of the body in the interaction without neglecting the connection with the mind and the situated and social nature of sport interactions. Moreover, despite what a reader could think, I am not particularly good at climbing; I usually climb sport climbing routes of 5th grade. This is due especially to the fact that I have not been very constant with the practice. Usually, I alternate periods of 3-6 months of practice to 3-6 months of pause, after which it is always very hard to restart. My difficulties are to be scared by the height and trust myself and my climbing partner. These difficulties helped me to develop a particular analytical approach to the sport also for personal reasons.

My experience of climbing has been crucial in the conduction of this research work. It facilitated the contact with institutions that organise courses, the recruitment of beginners and mountain guides, and the empathic understanding of the dynamics, the sensations, and the emotions expressed by the participants during the fieldwork interviews. Nevertheless, during the research process I have been rigorous in welcoming and giving equal attention and importance to opinions and experiences that did not resonate with my own personal experience.

Below, I report three personal experiences of climbing. Each of them illustrates a different environment or type of climbing. The purpose of such anecdotes is to show the dynamics of climbing and the different aspects pertaining to different sub-disciplines of climbing, which may be useful for the understanding of this thesis.

A usual day of indoor climbing. *It's winter and Guido and I decide to go climbing to Sanbapòlis, i.e. Trento climbing gym, after work. After changing our cloths in the changing rooms, we enter the gym. I have brought the rope and the Grigri, while we both have our own harness, climbing shoes, and chalk bag. We decide what route to climb among the few available. We choose an easy one to climb to warm up. It is a doable route also for me, so I will lead this one, i.e. I will climb first and put up the rope. I wear my climbing shoes, while Guido opens the rope bag and takes a free end of the rope. He passes it to me, and I pass it around the belay loop of my harness and close it with a figured-eight knot. He connects the rope in the Grigri and join it to the belay loop of his harness with a carabiner. We check with each other* *to verify that each the other has done her/his procedure properly because the safety of the climber depends on a well-done knot and on the right positioning of the rope in the belay device (in our case the Grigri). We both passed the partner's check and we are ready to go. I put my hands on the lower holds and I start climbing up. The holds are wide and deep, the so-called "jugs", and are very rough so there are no problems of grip. The wall is leaning so the effort is more on pushing with the legs than pulling with the arms. After a few movements I stop, grab the rope hanging from my harness, I pull it firmly to ask Guido to give me more of it and I pass it through the first quickdraw (in climbing gyms the quickdraws are already placed in the walls). I proceed like this until the end of the route where I find the chain. There, I pass the rope from both the carabiners hanging from the chain and turn my head to signal to Guido that I am ready to descend. He pulls the rope firmly so to make it so tense that is almost blocked, I 'sit', i.e. I hang on the rope with all my weight and I keep myself away from the wall by keeping my legs perpendicular to the wall. At this point, Guido lowers me to the ground by slowly releasing the Grigri lever.*

My first experience climbing at an outdoor crag. *For the very last lesson of the beginner course, we decided with the guide to go outdoors. The guide had chosen a crag with easy routes near Garda lake. After parking the car, we have to walk in the wood for about half hour. Climbing outdoor is interesting: the rock is cold when it is in the shade of the trees and very warm when climbing above the trees, it requires to find our own way on the rock without invading another route. Many times, I stop and wonder if a certain dip will be wide enough to put my feet on it and then pull up all my body. In some spots, the rock is very polished because of the many passages, its colour is different and it's slippery. And the routes are very long! In this crag they are 25 m on average, this makes it really difficult to hear the suggestions of the guide and to make me be understood by the belayer. The last route of the day is a little more difficult of the others. It has a hard start but the crux, i.e. the hardest sequence, is at the very hand. Here comes my turn to climb. I climb quite well for most of it, but when I arrive at the crux I struggle. After some attempts I start to feel distressed. I hear some voices from the ground, but I cannot understand the words. From the gestures I understand that I should not move on the right, but on the left. I can't see why: on the right there are plenty of holds. I don't know what to do, I can't ask to be lowered now because there are still quickdraws to recover. I try on the left, but I don't succeed going up. I stop, cry a little, I feel alone but I understand that the only way to get out of there is to arrive at the top. Then I restart going on the right and putting all my strength in the movements. I reach the top. I make large signs with the arms to the belayer to lower me. I put myself in the descending position. Breathe deeply. Look on the left: there is the sunset on the Garda lake.*

***My first experience of alpinism**. It's the dawn, we have already had breakfast and we have been divided in groups of three: two newbies with an instructor. I joined the alpine club section of Rovereto for their day trip in the Roda de Vael. They have just concluded an introductory course to alpinism, which I did not attend, but a friend who is an instructor there invited me to participate ensuring me that I could make it. We start walking towards the base of a cliff, which is the top of the mountain. At some point, the instructor who is with me stops and asks me and the other newbie: "Hey guys, where are we going?". We look at him surprised. It was a rhetorical question; he knows but we should as well. So, we look altogether at the topo. Once at the base of the rock wall, he asks a similar question "is this the starting point of the route?". Silence, bewilderment. It could be there, as well as 2 meters over there. He shows us how to recognise the starting point from the topo. Then we start to climb. My hands hurt because the rock is very cold, it's still early morning and we are at more than 2000m high. Some boulders that I want to grasp move, requiring a more careful and slow climbing. The gear to be used is different from that used in sport climbing, and the knots as well. I am grateful to a friend who texted me the night before saying: 'review the knots'. Luckily, the instructor, who is leading all the pitches, is almost always visible, so that the communication about when to start climbing to reach him are easy. After two pitches we need to walk a bit to reach another starting point. When we reach the second wall, we start inspecting it. Something is different from the topo. The instructor starts climb it, but then he comes down. There seems not to be a route there. (Then, once we are back to the refuge, the manager told us that the part of the mountain that we wanted to climb had collapsed two years earlier). We decide to climb another route nearby. When I arrive at the top I am happy but also tired from all the tension of the many pitches. Once at the top I find out that the arriving point does not coincide with the rappel point. The rappel point is 15 metres on the right. To reach it we need to walk on a corridor of rock large 1 m, with no walls on the sides, looking at the refuge where we slept that is tiny. My nerves collapse, I am scared but with the help of the others I manage to reach that distant point. After that, rappelling was a child's play.*

1.7 Outline of the Thesis

The thesis will unfold as follows: the next chapter presents a review of the existing research in HCI for sports, design of wearable devices in general and specifically for the sports domain. In chapter 3, the fieldwork aimed to understand the climbing practice is described, which consisted in fieldwork overview (section 3.1), observations (section 3.2), interviews with beginner climbers and mountain guide (section 3.3), and two focus groups (section 3.4) and the results presented in the form of a Design Space (section 3.5). In Chapter 4, the design process will be presented in its different steps of an explorative co-design workshop (section 4.2.), technological exploration (section 4.3.), and contextual co-design workshop (section 4.4.). Chapter 5 presents the conduction and the results of the assessment into the wild of the prototype created. In Chapter 6, the contribution of this thesis will be discussed. In Chapter 7, the thesis concludes with a summary of the work and a reflection on the limitations and the possible future unfolding of this research.

02 Related Work

2. Related Work

This chapter presents previous HCI research in the fields of sports and design of wearable devices (both in general and specifically for sports). The first section describes the works that so far have tried to define the scope of HCI research in the sport domain and highlights the state of the art of HCI research in outdoor sports in general and specifically in climbing; the second section presents research works that propose design principles for the design of wearable technology; the third section focuses on HCI studies on wearable devices for sports and clustering them in three categories according to the purpose of the device: *supporting physical performance*, *enhancing the sport experience*, *facilitating the social interaction*. Finally, the chapter concludes with a section presenting wearable devices created specifically for climbing.

2.1 HCI and Sports

In the last ten years, part of the HCI research became interested in the world of sports. This encounter produced two different kinds of works, those taking inspiration from the characteristics of sport to design systems that require a whole-body interaction and those trying to define research the themes to consider when designing technology supporting sport activities. The work of Tholander and Johansson (2010) belongs to the first group and identifies a series of qualities to consider for the design of movement-based interactions. By investigating people playing golf, skateboard, or BodyBug, they found a great connection between the artefacts used in these sports and the experience people make of the surrounding environment. To the second group it belongs the work of Müller et al. (2011) who identified four different levels of engagement that a person experiences during the physical exertion required by a sport and which could be of inspiration for the design. These four levels of engagement are the responding body (i.e. the physiological answers of the body to the exertion), the moving body (i.e. the muscles changing in order to perform a certain movement), the sensing body (i.e. the body reactions to the stimuli of the environment), and the relating body (i.e. how people might relate one another through digital technology). From a workshop conducted at CHI'14, Nylander et al. (2015) drew a series of design themes where together with body-related themes such as feedback, bodily awareness and control, and skill development, also 'sociality' appeared. The theme of 'skill development' is also at the base of the design sensitivities proposed by Jensen et al. (2014) for the design of interactive sport trainings, and at the base of the system designed by Fogtmann et al. (2011), which was inspired by the potential of kinesthesis (i.e. the internal awareness of the positions and movements of the body in the space) and aimed to help athletes gain the skills of anticipation and decision-making through Kinaesthetic Empathic Interaction.

In the last few years, some initial studies have started to investigate the sport practice (although not framing it in these terms) in order to widen the possible design space of technology for sports. By investigating the needs of advanced amateur runners to inform the design of motivational technology, Knaving et al. (2015) found that the life of runners participating in long races is complex and includes many aspects revolving around the competition, such as coordinating training with family duties, manage recoveries from injuries and the fatigue. Consequently, they found that, besides flow, many other elements help sustain runners' motivation, e.g. festival, whose large participation make runners feel more empowered and less lonely, competition, practicalities, togetherness, support from the audience. The authors come to the conclusion that technology should help runners craft their own experience of the race. Havlucu et al. (2017) investigated the lack of use of activity trackers by lonesome tennis players and discovered that these athletes would like to have specialised wearables able to provide detailed information about the tennis performance and to elaborate qualitatively the data perceived in order to give tailored suggestions. Moreover, they would like to be supported also from a cognitive point of view, e.g. by being helped to manage anxiety or to find motivations in the moment of discourage. These authors invite to consider the contextual differences of different sport communities.

2.1.1 HCI and Outdoor Sports

As the many conference workshops demonstrate (Daiber et al., 2017; Häkkilä et al., 2017; Jones, Anderson, Häkkilä, Cheverst, & Daiber, 2018), in recent years a certain interest has developed in HCI to investigate the specific topic of outdoor sports. So far, HCI studies focusing on this domain have reflected especially on the *role* that technology could play in this type of sports, which means, what kind of support it could provide and how. Ahtinen et al. (2008) explored the potential role of a mobile app for outdoor sports tracking. They categorised the technology for sport reported in the literature according to the four roles of 'logger', 'virtual personal trainer', 'gaming and entertainment', and 'community and social sharing'. Through their study, the authors found that outdoor sportspeople welcome an app for activity tracking in the form logger and personal diary because it allows to challenge with self over time, but the features of social sharing are not equally valued. Tholander and Nylander (2015) moved the focus from the measurable performance to the experience of performance, by highlighting the effects of the outdoor environment on the internal and external sensations of who practice them. People who practise this kind of sports seek the pleasure from being immersed in nature, but also the not-so-pleasant sensations of pain, sweat, fatigue, cold, that characterise the experience. According to these authors, the current design challenge of wearable and mobile devices consists in creating a technology capable of tackling other aspects in addition to the measurable performance, such as the personal lived experience of the sportsperson. Cheverst et al. (2018) highlighted the importance of mastery on the environment in mountaineering as an internal motivation to practice the sport and to comply with the rules given by the community of practitioners. In such context, a technology aimed to reduce the technical skills needed in the performance would be perceived as a way of cheating, while technologies aimed to register the performance and to prove it to the others would be accepted. Desjardins et al. (2014) investigated the perception of technology designed to provide support in situations of emergency, such as avalanche beacons, where collaboration and promptness are fundamental to intervene and possibly solve the situation. Similarly, Müller and Pell (2016) articulated four possible roles for technology in adventure sports according to a categorisation of the possible events that may happen along two dimensions: 'expected – unexpected' and 'instrumental – experiential'. The roles identified thanks to these two dimensions are 'coach', which includes the technology providing guidance in expected situations for a better performance during the adventure; 'rescuer', providing emergency services during unexpected events, for example an avalanche beacons; 'documentarian', for recording the expected events of the adventure with a high experiential value; and 'mentor', supporting the adventurer for reflection providing additional information to the felt experience during unexpected experiential events in order to gain a better understanding of what happened and pave the way for personal growth.

2.1.2 HCI for Climbing

Technologies developed for climbing can be grouped in two main clusters: augmented walls and wearable devices. So far, the majority of HCI works enhancing climbing walls aim to augment the experience of climbing by providing new patterns to follow or creating games. Liljendahl et al. (2005) augmented the holds of a climbing wall with LEDs, capacitive sensors, and sound actuators so that climbers by moving up the wall could recreate a melody. Other works used projections on the walls, thus creating Augmented Reality systems. For example, Wiehr and Kosmalla (2016) proposed Betacube, a self-calibrating projection system that can automatically create routes on every climbing wall and record and replay the climber's performance. Kajastila et al. (2016) created climbing games by combining body tracking through cameras and playful projections such as temporary goals on the climbing walls. Daiber et al. (2013) addressed the collaborative dimension of climbing by implementing an AR mobile app that allows groups of climbers to collaboratively design boulder routes on a training board. Lately, also Virtual Reality has found his way in order to augment the experience of indoor climbing. Dufour et al. (2014) created 'Ascent', a VR game that recreate the immersive experience of ice climbing into snowy mountains, while in order to have an even more immersive experience Kosmalla et al. (2017) paired the immersive experience of VR with the haptic feedback provided by an artificial climbing wall.

Conversely, the majority of HCI studies which investigated wearables for climbing have been designed to track the movements and assess the performance of elite climbers during their workouts in indoor gyms. The most widespread method to measure climbers' performance is by tracking their movements through sensors, typically with Inertial Measurement Units (IMUs), and then offering a visualisation after the ascent. Pansiot et al. (2008) developed ClimBSN, an ear-worn accelerometer whose data were then interpreted as motion fluidity, strength and endurance. Similarly, Ladha et al. (2013) designed and evaluated ClimbAX, a wristband able to detect the power, control, stability, and speed of a climber. Kosmalla et al. (2015) designed and implemented ClimbSense, a system compound of two wrist-worn devices that allowed the automatic recognition of the route climbed and the subsequent comparison of training sessions between climbers. Conversely, Feeken et al. (2016) built a system aimed at supporting beginners in improving their climbing technique and in particular to use more their legs. They combined the information provided by pressure sensors in the insole with a vibrotactile feedback on the ankle in order to give feedback in real time. When the sensors detected little pressure or hasty movements, the system would signal the errors to the climber in real time by means of two different kinds of vibration.

Regarding the experience of climbing, so far little has been investigated with respect to the design of wearables. A representative work is that of Schöning et al. (2007), who, by moving the focus of research from the indoor to the outdoor practice, shifted the purpose of wearable devices from performance assessment and learning to context-related needs such as location finding, communication between climbing partners, and knowing weather conditions. In order to address these needs, the authors proposed a concept based on Location-Based Systems and Augmented Reality, which provides information embedded in the climbing gear. The two different contexts of practice, indoors and outdoors, have been demonstrated to have a strong influence in the attitude of climbers towards wearable technology. Indeed, through a survey on the acceptability of activity trackers in climbing, Daiber et al. (2016) found that while outdoor climbers are more interested in fun and recreation than in performance, indoor climbers are keen on performance and competitiveness and would be interested in monitoring themselves. Deepening the investigation on acceptance of wearable devices, Kosmalla et al. (2016) conducted a survey on the preferred location on the body to receive feedback in real time and found that climbers would prefer on a wrist-worn device. Lately, from a test of different feedback modalities they found that sound was the one performing better directly followed by vibration, while visual stimuli was not appropriate since the visual attention of the climber was focused on the route.

Previous HCI research on wearable devices for climbing focused on supporting the performance. The works exploring whether climbers would accept to use wearables in their sport activity conducted their investigation mainly through intention of use, concepts proposal, or prototypes tested in controlled conditions. Conversely, the work presented in this thesis aimed to produce a wearable device grounded in the practice of the sport. Therefore, the research process required first to study the sport in-situ, involve climbers in co-design workshop, and evaluate the prototype in the realistic situation of a climbing lesson.

Overall, the works presented in this section provide a first attempt to analyse dynamics and characteristics of sports and to base the design of sport technology on them. The majority of these works focuses on the reactions and the needs of the moving body; only a minority of the most recent works offer an initial reflection on the sport practice and the role that technology could play in it. The work presented in this thesis resonates with the most recent works in acknowledging the importance of the role and the kind of support that technology can provide to outdoor sports and aims to ground the design of such technologies on the investigation of what elements constitute the sport practice considering the performance as well as the lived experience of it.

2.2 The Challenge of Designing Wearable Devices

Designing wearable devices is particularly challenging because of the direct relationship these artefacts have with the human body. Indeed, wearables are meant to be worn in direct contact with the body, while people are engaged in different activities and contexts. Therefore, the design of wearables raises several challenges related to ergonomics (e.g.

adapting to the body in movement) and usability. Moreover, as with all artefacts that decorate the body and are visible to others, they can be both intimate and representational Viseu and Suchman (2010), influencing the wearer's identity and social appearance simultaneously. Consequently, the design of wearables raises challenges also related to the representation of self and cultural acceptability.

Nevertheless, exactly for this close relationship they have with the human body, wearable devices are appointed with a great potentiality. In his seminal work, Mann (1997, 1998) presents wearable devices as a personal, prosthetic, private technology, controllable by the users and able to provide them with *constancy,* being always on and exchanging information, *augmentation* because they are not supposed to interfere with the main tasks but to augment human abilities, *mediation* of the information flow between the person and the exterior. This positive vision has lasted over the years and can be found in much more recent works, which affirm that, when well-designed, wearables might be perceived by their wearer as an extension of their body (Tomico & Wilde, 2015) that provides an augmentation of its native capabilities (Viseu & Suchman, 2010).

A few studies have tried to identify the design principles that allow the building of wearable devices that are comfortable, usable, and meaningful to the users, paving the way for the acceptance and long-term engagement of users with them. Rantakari et al. (2016) considered the users' perspective by investigating through a survey what product design features people would value the most. They found that the battery duration and the comfort of the device were people's main concerns, while the possibility of sharing and comparing personal data with others were the less interesting features. Conversely, Motti Genaro and Kaine (2014) identified 20 general design principles that influence users' acceptance and long-term engagement with wearables by analysing the literature on wearables. These principles are based on a human factor perspective and refer to both hardware and software aspects. Among other things, they involve *aesthetics*, *comfort*, *contextual awareness*, and *reliability*. Harrison et al. (2009) addressed the problem of the usefulness and the usability of wearables by investigating how effective they are in conveying information depending on the position on the body they covered. They evaluated the reaction time to a visual stimulus located on seven different body parts and found that it depends not only on the accessibility of peripheral vision on each body part but also on the activity that the person is performing when processing the stimulus. Gemperle et al. (1998) have mapped the design space of wearables focusing on the problem of *dynamic wearability*, i.e. the understanding of the human body areas where solid and flexible forms can rest according to the changes due to the movement.

Dunne et al. (2014) coined the term *social wearability* by extending the concept of the physical comfort of wearing technology to the idea of social comfort. According to this author, the social acceptance of a person wearing a device might depend on the aesthetics of the device as well as on the kind of interaction it requires. If gestures are required to interact with the device, there should be a balance between the distinctiveness of a gesture required for it not to be performed by mistake and the social consequences such gestures may entail. The importance of aesthetics and the symbolic value of wearing an artefact has been encountered also by Pakanen et al. (2016) while designing a smart handbag. From the co-design process organised by the authors, it emerged that bags are considered wearable artefacts and pertain to the world of fashion. Therefore, technology should not break the aesthetic value of the bag, which is conveyed by its materials, but rather be an enhancer of these qualities by helping it to adapt it to the different contexts. Similarly, by comparing the possible different shapes of an activity tracker, Lappalainen et al. (2016) found that rings are invested of a higher symbolic values compared bracelets: they are intended to be a piece of jewellery and to be seen, while bracelets can be more discreet. In this regard, Tomico and Wilde (2016) outlined the importance of considering the wearers' perspective and the diversity of meanings that can be generated according to their personal values, besides the comfort on the body, the context of interaction and the activity to be performed.

The works summarised here well represent the multifaceted issue of designing wearables, which requires considering product design and ergonomics aspects for the adaptability of the device to the moving body; perceptual aspects for a proper interaction with the device; aesthetics, values, and self-representation for the social acceptance of the wearer. This thesis took into account all these aspects in the design phase and orchestrated them with the requirements emerged from the sport practice analysis.

2.3 Wearable Devices for Sports

In HCI research on sports, wearable devices have been employed mostly to support workouts, enhance the sport experience, and facilitate social connections. This section presents HCI studies in this domain categorised on the base of these three main research trends. For the sake of clarity, it is necessary to specify that being the focus of the overall thesis HCI for sports, this section will not consider wearable systems for activity recognition only, i.e. systems provided with sensors able to capture data but without an interface to communicate this information to the sportsperson or to any other stakeholders involved in the sport activity (e.g. coach, audience), nor technologies designed to measure physical activity in general, such as pedometers.

2.3.1 Supporting Physical Performance

The most common wearable devices for sports are activity trackers, which are composed of wearable sensors and a visualisation system that allows users to monitor the progress of their performance. They have been mostly used for self-awareness; indeed, they have the double function of (i) a 'magnifying glass' capturing information from sportspersons' bodies and (ii) a communication tool that returns pieces of information to the wearer. HCI studies investigating the use of activity trackers focused on the effectiveness of the data presentation. Zhao et al. (2016) proposed an app that gathers the data streamed by a wearable and insert them in a gamification system aimed at increase the sportsperson's motivation. Alhonsuo et al. (2015) created concepts of a smartphone app to show data to young hockey players in order to provide them with guidance for a general wellbeing, rather than only awareness.

The capacity of wearable devices to detect performance in real-time has raised challenges also about how to provide effective feedback in real-time, not just after performance. Real-time feedback would enable sportspeople to adjust their movements while performing them, but, in order to be really effective, it should not distract the sportsperson or exceed her/his optimal cognitive load. Many studies have demonstrated the relevance of considering activity-related and context-related constraints when deciding what real-time feedback modality to adopt. Some studies explored different modalities of subtle feedback that could be conveyed through wearables, for example Bächlin et al. (2009) compared audio, visual, and vibrotactile feedback to determine the most appropriate modality for swimming. Participants were told to change swimming behaviour when they perceived a signal and the experiment showed that audio elicited the longest reaction time, probably because there is noise in the water due to the swimmer's movements. Hasewaga et al. (2012) explored sonification of skiers' centre-of-gravity to guide novices to adopt a correct body posture, demonstrating that with bio-feedback they are able to overcome the fear of speed and improve the experience of learning.

A considerable amount of attention has been paid to vibration as a feedback modality. Spelmezan (2012) deployed a network of vibrotactile motors on the body of beginner snowboarders to signal the right moment to turn with the snowboard. Similarly, Stewart et al. (2014) created TapTrain, a wrist-worn prototype for roller derby skaters aimed at giving feedback about their speed. In this case, the feedback was not delivered automatically, but the skaters had to query for it by tapping the wrist pad twice. There was a vocabulary of vibrations to convey different meanings: the motors would vibrate fast if skaters were improving their performance or slower if not. Similarly, Cauchard et al. (2016) addressed the problem of how to convey different meanings using vibration and designed and evaluated Activibe, a set of 10 tactile icons for communicating progress towards an established goal, and found good results in recognisability tests.

Finally, one work distinguishes itself for having investigated wearability in sports. Franke et al. (2011) investigated the level of intrusiveness and annoyance of a vibrotactile wearable device for rowers by applying plastic boxes on the body locations where the wearables should be placed and asking rowers to try them during the activity. The devices received a positive feedback.

2.3.2 Augmenting the Sport Experience

In the last few years, wearable devices have been employed also to offer a more immersive and augmented experience of the sport activity. Typically, immersiveness is reached through the adoption of Head Mounted Displays (HMD), which provide the sport person with the view of an augmented or virtual reality. Examples of these themes of investigation are the works of Colley et al. (2015), who wanted to explore the effects of a blended reality in-the-wild. They built a system that allows skiers to see a virtual reality environment on an HMD while actually skiing and found that the sensorial mismatch between sight and kinesthesis provoked by seeing another landscape influenced the skiers' balance but at the same time increased other senses. Similarly, Fedosov et al. (2016) designed an augmented reality app to be visualised on the skiers' goggles, which allowed them to add user-generated content on ski area maps and to share this information with other members of the same ski group to support decision-making about which slopes to go or where to meet.

2.3.3 Facilitating Social interaction

Besides improving performance, HCI researchers have also explored the potential of wearables to improve social interactions in sports, in particular by increasing group awareness and social connection among teammates or augmenting the interaction between the sportspeople and their audience. In a few studies, group awareness was shown to improve sportspeople's performance and motivation. For example, Choi et al. (2016) created and evaluated an exergame for group training where swimmers are provided with group performance awareness through earphones and are required to collaborate or compete with others, while Mauriello et al. (2014) prototyped and evaluated a wearable e-textile display aimed at supporting training in groups of runners by providing awareness of the group's pace, the distance run and the wearer's heart rate. Similarly, Walmink et al. (2014) investigated the potential of displaying heart rate among cyclists to foster cycling partners' support during exertion, and Page and Vande Moere (2007) designed a system of wearable displays embedded in basketball players' jerseys which aimed to help players take in-game decisions by showing individual information (e.g. fouls, scores, time alerts). However, Page and Vande Moere's evaluation showed that the display system was more useful for the stakeholders outside of the game, such as coaches, referees, and the audience, rather than for the basket players.

Some other works pursued the social connection between sport partners using wearables as communication devices. In the seminal work of Weilenmann and Holmquist (1999), wearable devices were used to foster the communication between a group of skiers by providing them with continuous awareness of the presence of others. Müller et al. (2007) explored communication through wearables for connecting joggers who run individually in different places or at different paces. Their system aimed at influencing runners' motivation by allowing them to speak to each other through a headset and providing a spatialised audio so that runners could hear the slower person as she was at the back and the faster person as she was in front.

Finally, another branch of research in this domain explored the communication between audience and sportspeople. Tomitsch et al. (2007) conceived a system composed of wearables able to detect the clapping and cheering of the public and an LED public display to visualise the level of appreciation in order to enhance the participation of in-situ audience to sport events. Other works focused on how to make sportspeople feel the support of their specific supporters. Woźniak et al. (2015) focused on enabling long-distance runners to feel the cheering of their remote supporters individually. They created Rufus, a system that supports two-ways communication: the supporters could send three different messages, each associated with an LED colour on a wrist-worn device, signalled by a vibration; the runners could send feedback on received message by pressing a button. Similarly, Curmi et al. (2017) discovered that sharing runner's physiological data during a race encourages spectators to provide more support and creates a social connection between runner and her/his fans.

This section gathers the main studies in HCI investigating wearable devices for sports. The work presented in this thesis builds on these works but differs for the type of approach adopted. Starting from the investigation of the practices of a specific sport community, i.e. climbers, and adopting a co-design approach, this thesis aims to gain an understanding of the needs of the sport community within a comprehensive view of the sport practice and to offer a wearable solution that integrates with such practice.

In general, this thesis grounds on the works presented in this chapter, but it also differs from them because it adopts a Practice Perspective and a Co-Design approach. This thesis investigates the elements that constitute the practice of outdoor sports besides performance in order to identify the most appropriate role for technology designed to support this kind of sports. Moreover, this thesis aims to orchestrate the findings emerged from the analysis of the sport practice with the multifaceted issues implied in the design of a technology to be applied on the body (i.e. ergonomics, perceptibility, and social acceptance). Finally, it aims to provide the sport community investigated with a wearable device that is useful but also sufficiently open to be appropriated within the sport practice.

03

Understanding the Climbing Practice

3. Understanding the Climbing Practice

In this chapter, the first phase of the research work is presented. This phase was aimed to define the design space for wearable devices in climbing, through fieldwork.

3.1 Overview of the Fieldwork

To identify the design opportunities for wearable devices in climbing, the practices of this sport were explored at different levels: the difficulties of learning were investigated along with the habits of experienced climbers. A fieldwork was deemed the most suitable method for the exploratory nature of this data collection phase. There were four main strands to the fieldwork: observations, interviews with trainees, interviews with mountain guides, and focus groups with experienced climbers. The fieldwork was conducted over a period of six months, from March 2015 to September 2015. The overview scheme of the fieldwork with dates, venues, and number of participants is depicted in Table 1, while a more detailed description of the topics investigated, and the insights gained is presented in Table 2.

Study	Dates	Venues	N. Of participants
Observations	March 2015	Climbing gym at the sport center of Mattarello (TN) and Sanbapòlis, the climbing gym of Trento	8
Interviews with trainees	March – May 2015	Climbing gym, FBK, DISI dept. of University of Trento	11
Interviews with mountain guides	March – May 2015	Several different venues in town, usually bars	6
Focus groups	September 2015	FBK premises	15 (9+6)

Table 1. Timeline of the fieldwork.

The fieldwork started with the observations of a climbing course at an indoor gym in order to explore the situated practices of learning and teaching climbing in the ecological context where these activities typically take place. The course was organised by the University Association for Sports (Unisport) and took place at the gym of Mattarello (TN). The course involved nine trainees and one mountain guide and consisted of nine lessons. However, the last lesson was held in the Sanbapòlis, the climbing gym of Trento, because there the walls are higher and the routes more difficult.

Study	Dimensions investigated	Findings
Observations of 8 indoor climbing lessons	Teaching strategies Communication between instructors and trainees, and between climbing partners Trainees' difficulties	The 5 models of Contextual Inquiry: • Sequence • Flow • Physical • Artefact • Culture
Semi-structured interviews with 11 trainees	Motivation for taking a climbing course Difficulties encountered Mapping of the emotions experienced during the different phases of the activity Communication between climbing partners Risk-taking attitude Trust	Negative emotions: • The discomfort of the vertical dimension • Fear Coping strategies against fear Trust Coping strategies against mistrust
Semi-structured interviews with 6 mountain guides	Teaching strategies Course objectives and content Learners' most frequent errors Motivation for practicing climbing	Positive emotions: • Self-efficacy • Flow • Exploration
Two focus groups with 15 experienced climbers	Climbers' attitude towards technology and likelihood of acceptance	Individual values: expertise and self-challenge Community values: sense of belonging and pride Environmental values: safety and adventure

Table 2. Summary of the studies investigating the climbing practice.

Secondly, semi-structured interviews were conducted both with trainees and mountain guides to investigate their personal experiences in learning and teaching to climb and to gain an understanding of the symmetrical points of view of the actors involved on a climbing course. Both the interview series took place between March and May 2015. The interviews with the trainees involved overall eleven participants: seven from the course just observed and four from another course more focused on outdoor climbing, taught by one of the mountain guides interviewed. The interviews with the trainees were conducted either to the climbing gym just after the lesson or in Povo (TN), where some of the faculties of the University of Trento are, in case the participants were attending those faculties. In March 2015 also the mountain guide teaching at the Unisport course was interviewed, while the others were interviewed in May. The contact of the five mountain guides was provided to the researcher by a colleague from the same research centre (FBK). These interviews were conducted in places comfortable to the guides, usually in bars close to their homes. The focus groups were aimed to leverage discussions on the possibilities for using technology in climbing, based on the participants' different experiences. The two focus group involved 15 experienced climbers in total, recruited among FBK colleagues, their friends and personal acquaintances of the researcher. They were conducted within the premises of FBK at the beginning of September 2015.

The observations were inspired to the Contextual Inquiry method for what concerns the analysis but followed a different approach in the conduction. Rather than establishing a relationship of apprentice (the researcher) and master (the instructor and the trainees), it was preferred to conduct a non-participant observation in order to not interfere with the activity of the lessons. The interviews and the focus groups were audio-recorded and then transcribed. The data collected from all three studies were analysed through Thematic Analysis (Braun & Clarke, 2006) using the software Atlas.ti. In each study, Thematic Analysis was first used to elicit and compare emergent themes in order to identify and refine interpretative categories; in the second phase, the categories identified were compared with the research literature on the topic in order to explain the dynamics of the case study. The analysis started when the data was still being collected and has been an on-going process for all the duration of the fieldwork. This continuous process allowed us to refine the questions and directions of the investigation as part of the field study.

In the next sections, the findings of each strand of the fieldwork will be presented separately. Then, the findings will be merged and discussed altogether in the section concerning articulation of the design space.

3.2 The Practice of Learning to Climb

In this section, the procedure and the findings emerged from the observations of an indoor climbing course are presented.

3.2.1 Participants

The observations were conducted during the spring semester climbing course organised by the sports association of the University of Trento (UniSport). The course consisted of eight indoor lessons at a frequency of two lesson per week. It was delivered by a professional mountain guide member of the Italian Alpine Club as the instructor and attended by nine trainees (four males, five females, aged M= 26 years). Each observation lasted for the duration of the lesson, i.e. two hours, for 16 hours of observation in total.

3.2.2 Procedure

The observation methodology was inspired by the Contextual Inquiry method (Beyer & Holtzblatt, 2009) adapted for the specific context. Indeed, given the high risk of falls and injuries inherent to climbing, non-participant observation was preferred and the researcher's questions to the instructor and to the learners during the activity were limited. The researcher sat on the safety mattresses a few metres away from the climbing wall and observed the scene from the back or the side. To promote the climbing group's acceptance of an observer, the researcher wore climbing clothes and occasionally she was invited to climb a route or to help if a belayer was missing. The data was collected by filling in a grid drawn from the Contextual Inquiry models, but also by noting down the events that the researcher judged remarkable. Contextual Inquiry models were used as an analytical tool to organise and interpret the data collected. Photographs (approximately 150) and notes (about 35 pages) were taken during the observations and were later classified according to:

1. The SEQUENCE model, i.e. the detailed sequence of actions in the various activities observed.
2. The FLOW model, i.e. the communication stream and the coordination between the actors involved.
3. The PHYSICAL model, i.e. the physical organisation of people and artefacts in space.
4. The ARTEFACT model, i.e. the objects supporting the activity.
5. The CULTURE model, i.e. the values that influence the practices of the people observed.

These models were used to delineate the general activity model of a climbing course.

3.2.3 Findings

The sequence model: goals and structure of a typical climbing course. The ultimate goal of a climbing course is to prepare the trainees physically and mentally for the time they go climbing on their own; in the words of the teaching guide "*to provide experiential toolkit for when they will go climbing autonomously*". In practice, instructors pursue this goal by teaching their trainees the fundamental rules of safety, basic movement techniques, how to belay, how to acquire proprioception, balance, and trust, and how to lead. When trying to climb for the very first time, beginners do not yet know how to manage their bodies, and during the interviews all the mountain guides reported the same common errors. Usually, beginners tend to rely on the strength of their arms and pull themselves up rather than pushing with their legs, they rush towards the top rather than focusing on the technique, they are not aware of their body position and why they lose balance, and they do not trust small holds or the grip of climbing shoes. Therefore, instructors spend a lot of time teaching the basic movements of climbing, such as pushing with the legs instead of pulling with the arms, finding resting positions, and shifting the weight on the thrusting leg before starting to move. However, mental aspects of climbing are considered too. For example, instructors frequently remind trainees to focus on the climbing technique rather than getting to the top of the wall as fast as possible and urge them to pay attention to their internal sensations in order to develop proprioception, to improve through perseverance, and spur them to braveness and trust.

The climbing course observed by the researcher followed a spiral progress, being cyclic and evolutionary at the same time. All the lessons shared the same sequence of activities aimed at the ultimate goal of making climbers independent, but the content of such activities changed every time to increase the level of difficulty of the activities and adapted to the difficulties of the trainees (for a pictorial overview, see Figure 3). The lesson started with a preparation phase where trainees put on the climbing gear while the instructor set up the ropes on the walls. When everything was ready, the instructor would recapitulate what was told during the previous lesson and outline the current lesson. The main activity was a succession of ascents (usually four), each one with a different focus, e.g. 3-steps progression or trusting the belayer. Every ascent shared the same sequence of actions: they started with the explanation of the goal of the exercise and demonstration of the movements sequence by the mountain guide, and this was followed by the practice. For the ascents, the trainees were put into pairs so that one would climb while the other would belay, then, when the first partner had completed their climb, they exchanged roles. Usually, trainees' mistakes during the first exercise would trigger a loop of explanation and demonstration of proper movements and techniques as the basis for a new exercise. Finally, the lesson usually ended with some bouldering. At this stage, there was a change in the style of the lesson; it was a more social atmosphere where the trainees were no longer organised in pairs but sat all together on the mattresses and everybody could suggest movements or challenges to the person climbing the bouldering wall. The lesson was then concluded with a recap of the teaching delivered.

Figure 3. Main sequence of a climbing lesson.

The flow model: communication between climber and belayer. Normally, during the ascents the climber communicates her/his needs to the belayer through a series of conventional commands, e.g. "*take!*" when the climber wants to rest; "*slack!*" when s/he needs to clip the rope; "*watch me!*" when trying a difficult movement; and "*lower me!*" when, finally, the climber gets to the top. On the other side, the belayer communicates to give suggestions to the climber, asks for feedback about the climber's wellbeing, and encourages her/him. Yet, as for the instructors, there can be communication difficulties due to the physical distance, which can prevent climbing partners from seeing and hearing each other ("*I turn my head and I tell her, shouting. Even if sometimes it's a bit tiring and I'd prefer her to hear without requiring me to turn my head*" - T1 – climber). To overcome this problem, usually climbing partners speak loudly or through gestures like 'thumbs up' when arriving at the top of a climb. Then, as both climber and belayer become more experienced, part of the communication for coordination becomes non-verbal and is conveyed through the rope. When the climber needs to clip the rope in the quickdraws, s/he simply pulls up the rope to signal her/his need, and an attentive belayer would be ready to give her/him slack and not to make her/him tired with several attempts. The tension of the rope is also used by the belayer to signal her/his presence when the climber is climbing in top rope. By keeping the rope tense and using it to accompany the climber's movements, the belayer communicates that her/his attention is totally dedicated to the climber.

The physical model: a vertical world. Notably, the physical space of climbing has both a vertical dimension (the wall to climb) and a horizontal one (the ground). The vertical area is occupied by the climbers and is dedicated to the action, where trainees experience the sensations and the challenges of climbing, and usually there is little communication (usually only for doubt resolution or suggestions). The horizontal area is where the belayers and the instructor stand during the climber's ascent and the place dedicated to explanations, reflections, observation of the gear, etc. During the lessons observed, typically the instructor would follow the climbers by standing on the ground next to the belayers, so that he could intervene if needed (Figure 4).

Figure 4. Instructor observing the trainees during a climbing lesson.

At times, the instructor mixed these two dimensions, for example when he climbed up to follow closely the climber's rope manoeuvre at the top or when he wanted to demonstrate some movements while explaining them.

The artefact model: enhancing trainees' sensorial awareness through auxiliary artefacts. All the artefacts used during the lesson were provided by the instructor, so that the trainees did not have to make a financial investment before knowing if they liked the sport. These artefacts fall into two categories: those necessary for the activity and those in support of teaching. The artefacts necessary for the activity were the harness, the rope, the climbing shoes, a friction device (in the lessons observed they used Petzl Grigri 2), a locking carabiner, and chalk; while the artefacts for teaching support were gloves, wooden blocks, strips of fabric, etc. used for exercises with specific goals.

Moving away from the usual motor schemes is psychologically demanding; beginners need to learn to feel confident in the vertical dimension. Therefore, the very first objective of a climbing course is to make trainees familiarise with verticality. In order to do this, instructors seek to foster trainees' first-hand experiences using special techniques and auxiliary artefacts to help them learn through direct bodily sensations. In the interviews, the guides affirmed that one of the aims of their teaching exercises is to help trainees gain awareness of implicit or hidden mechanisms of their body in movement, by revealing them. For example, they ask trainees to walk on tiptoes along wooden blocks, with a hanging weight tied to their harness, to visualise the shift of the centre of gravity with the lateral swing of the hips. Other exercises are designed to deprive or limit some perceptual abilities in order to intensify some others through the use of body constraints, e.g. climbing while wearing ski gloves or keeping a hand behind the back in order to reduce the grasping capability and the instinct to pull yourself up with the arms, and at the same time to increase balance skills. Furthermore, to help trainees gain the dexterity needed to clip the rope in the quickdraws as leading climbers and help them familiarise gradually with the changes in balance occurring when performing this action, sometimes instructors made trainees clip an auxiliary rope while climbing in top rope. The general purpose of these exercises is to develop proprioception, i.e. kinaesthetic awareness. By modifying the usual perceptive channels, the guides help them to focus on how they move, find balance, and gain self-confidence. Indeed, each exercise is usually followed by the instructor's questioning about the trainee's personal sensations "*How was it? How did it feel? It is better this way, isn't it?*".

The Cultural Model: getting ready for the 'real' challenge. Besides the movements, the instructor talked about values connected to the risks entailed by climbing. Sometimes, these values were contradictory. On the one hand, he promoted pride in the practice, for example inviting the trainees to try to avoid catching hold of the quickdraws webbing (A-zero technique), asking for a rest to the belayer, calling the Alpine rescue but knowing the basic techniques and rope manoeuvres and being capable of judging dangerous situations; and on the other hand, he fostered humility in knowledge, urging trainees not to be shy and always to ask for clarifications whenever they had doubts before starting something. During the lessons, the guide also described mountaineering scenarios, presenting them as the 'real' challenge. According to this view, the climbing gym is a place to train and prepare, while the mountains and cliffs outdoors are the place to tackle the real challenges offered by the real rock. The instructor talked about some important alpinists who climb in order to explore and who have contributed to the evolution of the gear and climbing techniques, widening the frontiers of climbing.

3.3 The Experience of Learning to Climb

In order to investigate the personal lived experiences of learning and teaching to climb, semi-structured interviews were conducted both with trainees and mountain guides. The main goal was to gain an understanding of the symmetrical points of view of the actors involved on a climbing course. To this end, the interviews with the trainees investigated their motivations and objectives in practising a sport such as climbing, the main difficulties encountered during the learning, their personal attitudes towards risk and trust, and their emotional involvement. While the interviews with the mountain guides were aimed at understanding the goals, the content and the structure of a climbing course, the issues encountered most frequently, and the teaching strategies enacted to cope with them. Finally, they were asked to reflect on what they like most about climbing and their job.

3.3.1 Participants

For the interviews with the trainees, eleven beginners (four males and seven females, aged M= 24 years) with widely varying levels of climbing experience (M= 21 months, SD = 27.8 months) were recruited. The wide difference in the level of climbing experience was due to the fact that many interviewees had actually started to climb when they were kids and at the time of the interviews were attending a course because they wanted to restart. Seven of them were attending the indoor course we observed, while four were attending a rock-climbing course, which was more focused on outdoor climbing.

For the interviews with the mountain guides, six participants were recruited (all male, aged M= 37 years; years of work as mountain guide M= 8). One of them was the instructor at the indoor course where the researcher conducted the fieldwork observations, while the others were recruited among personal contacts. Although in Italy climbing courses can be taught either by certified instructors affiliated to the Italian Alpine Club (CAI) or by Professional Mountain Guides, it was decided to interview mountain guides because they are the only professional figures who teach mountain sports for work, whereas CAI instructors teach as voluntary work.

3.3.2 Procedure

The interviews with the trainees were conducted individually and lasted approximately 30 minutes each. During these interviews, emotions were investigated in two different ways. First, interviewees were asked an open question about which emotions they associated with climbing, and then they were asked to fill in a table (on a document) showing a set of possible emotions and a sequence of actions involved in an ascent, both for climbing and for belaying. In this task, participants had to select the emotions they felt at every step of the activity. They were allowed to select none, one, or more emotions for each action and were asked to explain their choices. The explanation was recorded and later transcribed as part of the interview. The purpose of this task was to understand which emotions are typically recurring and which moments are the most difficult for the trainees. The emotions presented to the participants reflected the classification proposed by Russell in the circumplex model (Russell, 1980). According to this model, emotions can be arranged on a wheel, which represents the progressive variation of valence (i.e. pleasantness) and arousal (i.e. intensity) in the continuum of emotions. For the purposes of this study, words representing three emotional states were located in each quarter of model, giving rise to opposing pairs of emotion across the circumplex model (see Figure 5). The selection of the most widespread and relevant emotions experienced during the climbing performance was made by the researcher on the base of her direct personal experience and the discussion with other climbers.

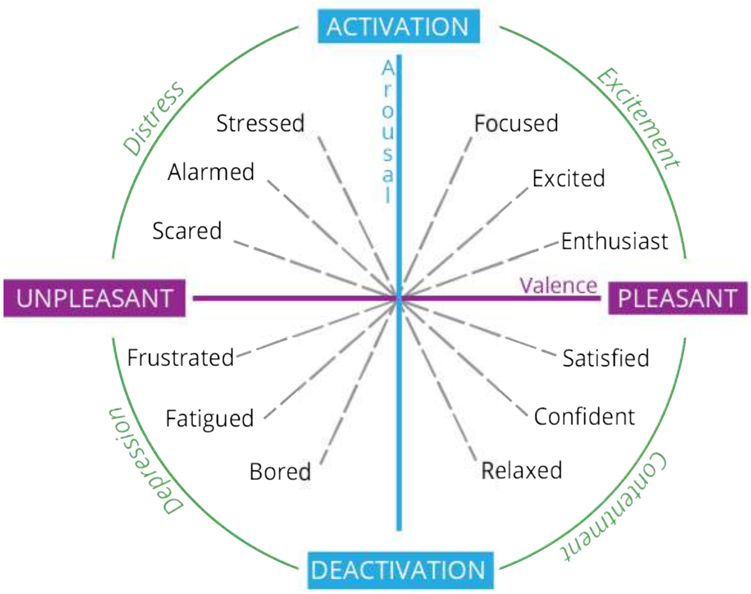


Figure 5. Russell’s circumplex model adapted to the case study of climbing.

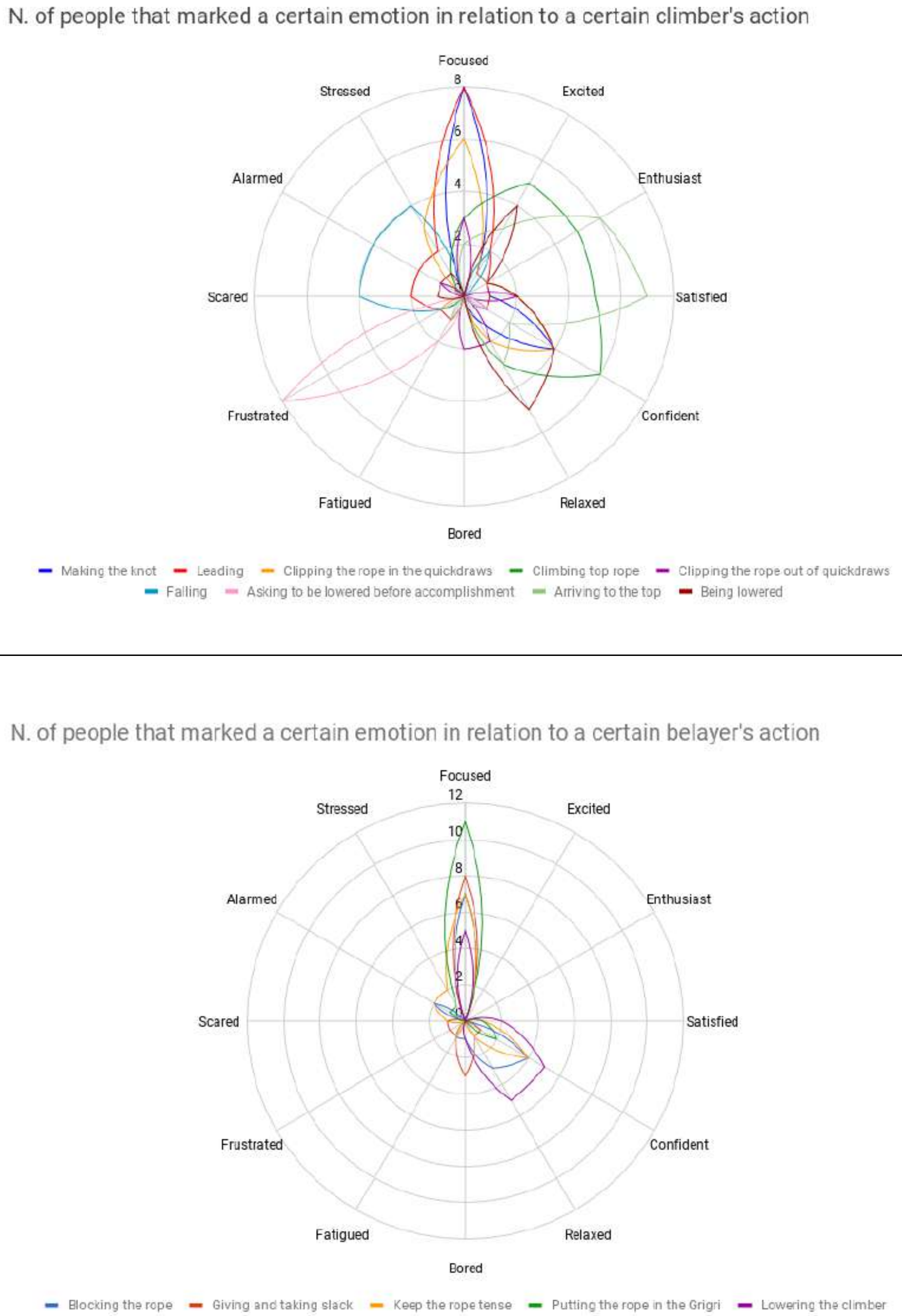
The climbing actions to be matched with emotions were: making the knot, leading, clipping the rope in the quickdraws, climbing in top rope, clipping the rope out of the quickdraws, falling, asking to be lowered before completing the climb, getting to the top, being lowered. The actions for the belayer were: putting the rope in the Grigri®, giving/taking slack, keeping the rope tensed when the climber is in difficulty, making the climber rest, lowering down the climber. When reporting the results, this task will be referred to as 'the emotion-action matching task'.

The interviews with the mountain guides lasted approximately one hour and were conducted at different times and different places. The researcher met the mountain guides where it was more convenient for them, usually at bars near where they lived.

Quotations from the interviews are anonymised: trainees' quotations are identified as T1, T2, T3, etc., whereas mountain guides' quotations are identified as MG1, MG2, MG3, etc.

3.3.3 Findings

From the interviews, it has emerged that at the beginning climbing is mostly an emotional experience. The vertical dimension where the climbing activity takes place requires the acquisition of new specific motor skills, which is made even more difficult by the emotions provoked by the risk of falling. On the other side, the overcoming of such psycho-physical difficulties and the accomplishment of a route are a source of great satisfaction. Here below two radar graphs summarise the results of the emotion-action matching task and provide an overview of the emotional engagement entailed by climbing. The two radar graphs reproduce Russell's wheel and show the emotions in the same order. The coloured lines shows which emotions have been marked by how many people during each action as a climber (figure 6a) and as a belayer (figure 6b). At a first glance, from these two graphs it is possible to note that 'focused' is the most common cognitive state in climbing. The term 'focused' was marked by eight participants for the actions 'leading' and 'making the knot' as a climber and, to different extents, for all the activities as a belayer. For the rest, the wheel of belayer's emotions (Figure 6b) reports only a few remarkable entries (5) for 'confident' and 'relaxed', which mirror the climber's status. Indeed, 'confident' and 'relaxed' have been marked in relation to the action of 'lowering the climber'. Conversely, the wheel of the climber's emotions presents more variety of emotions. The positive ones relate to 'arriving to the top (of a climb)' (light green light) and climbing in top rope (dark green), eight people affirmed that they would feel frustrated when not able to accomplish a climb (pink line) and five people affirmed to feel relaxed while being lowered by the belayer, while the item ‘falling’ elicited the highest scores for the three emotions in the distress quarter of the model (‘stressed’, ‘alarmed’, and ‘scared’) with four entries each (See Figure 6a).



a)

b)

Figure 6. The emotions triggered by the actions performed as a) climber and b) belayer.

In the following subsections, the emotional states that characterise climbing will be explained in detail, as well as their influence on the performance and the coping strategies enacted to overcome them.

3.3.3.1 Positive Emotions

People who choose to practise this sport seek the positive emotions it can bring about. Climbing can give great satisfaction and a sense of achievement when the climber is able to overcome her/his motor difficulties and fears (as T11 stated: "It gives a good sensation in general. You look down and you see how far you have done, and you feel satisfied for having overcome the difficult steps and fear"). The main sources of satisfaction in this sport are i) the sense of self-efficacy generated by overcoming the challenges that climbers pose to themselves by tackling the rock; ii) the sense of flow, which consists of complete absorption in the activity and the liberation of the mind from other thoughts; and iii) the sense of exploration, i.e. the awareness that because climbing requires skills that not everyone masters, it enables those who practise it to reach places accessible to few people. In the next paragraphs, the experience or the expectation of these positive emotions (according to the level of experience of the interviewees) are reported in detail.

Self-efficacy. Notably, climbing does not involve any support tool for the activity other than special shoes. The gear used is meant to ensure the climber's safety, but the rock wall is tackled just with the body, through the skilful use of strength and movement techniques. The direct relationship with the rock and the use of the body as a tool were revealed by T1's words when she stated, "the beautiful thing, in my opinion, is that you feel you go up thanks to your body, to your limbs; you do things with your hands, you perceive that it's you who is doing that". This sense of agency on the rock was sought by the trainees who enrolled in the course ("[I enrolled on this course] to master a new way to arrive at the top of a mountain" - T7). Nevertheless, every ascent is a challenge to yourself ("It is a challenge to yourself" - T4, "It challenges your limits" - MG5) and it can bring a great sense of satisfaction and self-efficacy when you are able to overcome the difficulties you encounter ("You struggle, but, in the end, you reach a goal" - T10; "The satisfaction to have reached the top" - T8), but also of frustration if you fail. Indeed, during the emotion-action matching task, trainees marked 'getting to the top' and 'being lowered' with the positive emotional states of relaxation (5), confidence (4), excitement (4), and satisfaction (2), while 'asking to be lowered before accomplishing the climb' was matched with 'frustration' by eight participants out of 11.

Flow. Climbing involves several levels of difficulty and every climber can choose the level of challenge that best matches her/his skills. An engaging climbing route requires climbers to dedicate all their physical and mental resources to it. In the emotion-action matching task, 'focused' was marked by the majority of participants in relation to all the actions involved, providing evidence that focus is the key mental state of climbing. When climbers are on an ascent which engages them with the right level of difficulty and without stressing them excessively, they become totally absorbed in the activity and isolated from the rest, in a condition of flow

> *"[When I climb] I'm at home, I feel at ease, and the world doesn't exist anymore; only the 4sqm where I'm moving exist, [and they appear] as I move along them. In this sense, climbing is liberating. It is my corner of paradise. I feel good when I climb even if I snort because it's difficult" (MG2),*

> *"At times, you are so much focused that everything else goes to the background and you don't hear people around shouting or anything else" (MG1).*

The absorption in the 'here and now' works as liberation of the mind, e.g.

> *"It requires you to focus a lot and it works as a liberation of the mind from the problems of the day" (T5).*

> *"When you climb you are uncomfortable, you are forced to focus on the few centimetres of rock you have in front of your nose, you cannot think of anything else, so inevitably your head is clear" (MG3).*

Exploration. The ultimate goal of most of the beginners and guides interviewed was to climb outdoors, either on outdoor cliffs or multi-pitch routes. As T3 affirmed, "I'm trying to learn the basics so that then I can go climbing outdoors. The outdoors is the achievement of a goal, there you can arrive to the top and see all the mountains around have to offer." This fascination with the outdoors is due to climbing being considered not just a sport, but as an adventurous outdoor pursuit ("It's an adventurous sport" - T6). Indeed, usually indoor gyms are regarded as places where to train before going outdoors, because it is on the rock that climbers can fulfil the highest levels of self-challenge and adventure ("Climbing is beautiful when practised outdoors, in a natural environment. There it can entail its adventurous character" - MG5). Moreover, mastering climbing skills and getting the chance to put them into practice outdoors is seen as a kind of a privilege because it enables climbers to discover new places, accessible to few people.

> *"Climbing is exploring, going up to see what is beyond" (MG5);*
>
> *"You stay in the nature and you can see suggestive and unusual places" (MG3);*
>
> *"It brings you to visit corners of Earth that are reserved for a few. Even if many classic routes are crowded on Sundays and the rock is slippery, to climb is a privilege because it means that you feel well both physically and mentally, that you are in harmony" (MG6).*

3.3.3.2 Negative Emotions

While positive emotions become part of practice when climbers have mastered at least the basics of the sport, during the learning phase, beginners often experience negative emotions due to their lack of motor skills and the novelty of the vertical movement. The most common negative emotions are discomfort, stress, fear, and panic, and these can be seen as a continuum of increasing intensity. The following paragraphs describe the difficulties caused by the discomfort and fear provoked by the vertical dimension.

The discomfort of vertical dimension. Since vertical movement is not something that people typically deal with in daily life, learners experience a general feeling of uneasiness due to their clumsiness. MG2 made an interesting comparison when he affirmed

> *"this is exactly what happens to a child who is learning to walk. Why is s/he clumsy? Because s/he has to learn the sensations (...) and the beginner climber is in exactly the same situation, even psychologically because s/he feels unprotected, not because climbing is scary in itself, but because s/he is not able to recognise the sensations s/he feels".*

From the interviews with the guides, it emerged that beginners usually try to reach the top of a climb as quickly as possible in order to overcome their discomfort. Climbing, however, is about efficient and fluid movements, as shown in this short dialogue between instructor and trainee: MG1: "*C., what's your goal* [for this ascent]?" C.: "*Getting to the top...?*" MG1: "*Getting to the top is a trivial goal!*" During the interviews, the trainees confirmed that learning such movements is difficult, and explained that the challenge lies not only in the acquisition of the correct motor sequences, but also in the effort to overcome the fear that the execution of those movements entails ("*When there are difficult moves to do, I become demoralised and I never try*" - T8). Therefore, movements and emotional states are closely intertwined in climbing: on the one hand, some movements are scary, and, on the other hand, fear can drive climbers to move hastily or alternatively it can block them.

Fear. Sometimes, the feeling of clumsiness that beginners experience can rapidly turn into fear because, in addition to the novelty of the movement patterns, the vertical dimension implies objective danger. During the interviews, several trainees agreed that fear is the prevailing emotion while learning how to climb ("*Fear is the first that you feel*" -T8). Beginners perceive climbing (especially when leading) as an alternation of fear and relief. As the trainee T8 explained:

> *"Leading... focused, yes, a lot, it takes me longer to think of the next move and especially whether [holds] are good enough; scared a lot, then safe when I clip the rope in the quickdraws, in that moment I feel... relieved; then, when I move again away from the quickdraw, I start again to be scared until I clip the rope in the next one, so it's all an alternation".*

They fear injuries, heights, falls, and handling gear. The gear is a great source of stress for both climbers and belayers because the safety of the activity depends on its proper management; thus, it involves great responsibility.

Coping strategies against fear. In general, guides consider fear to be a normal, healthy, and intelligent response since it is a sign of the survival instinct. However, fear should be kept under control because when it grows into panic, it can hinder proprioception and focus, making climbers move too hastily or, conversely, preventing them from action. Apart from the familiarisation exercises described in the previous paragraph, guides are very careful not to force beginners to do things they do not feel like doing. According to guides, stress and fear can be overcome simply with inner motivation and will. Thus, the work to improve the management of stress and fear is left up to the individual's commitment

> *"I always say that climbing is more of a discipline than a sport because it unites the physical and mental aspects in an inseparable way. So, I wish that it is appreciated for the introspective research work that it forces you to do to overcome your fears, your limits. This introspective work is formative for the personality"* (MG3).

Conversely, when fear strikes, the guides must help the individual calm down and progress. Such situations are delicate and there are no codified rules to follow for assisting the scared trainee. The tension is solved in different ways every time, according to the instructor's mood and judgement, the nature of the trainee's reaction, and the social situation. After years of experience, the guides develop empathy that allows them to understand trainees' states of mind and to find the best way to engage with them. During the fieldwork observations, when climbers experienced fear, the guide intervened by talking to them and trying to bring their emotional state back to the calmness needed to make a fair assessment of the wall and to move properly (Figure 7). In these cases, the guide had to judge the type of help to provide, and his verbal messages could take the form of suggestions (e.g. "*try to move your right foot on the green foothold*"), instructions (e.g. "*outstretch your arms*"), reassurances (e.g. "*don't worry, you have almost arrived!*"), or encouragements ("*well done!*"). Regardless of type, every communication was quick and direct. As MG2 affirmed during the interview: "*I let them do and I correct them later when they have their feet back on the ground (...). When the climber is hanging, there is no room for rational discourses, just reassurance*".

Elaborating on the topic of reassurance, some of the guides said that although physical contact is potentially an effective solution to reassure frightened beginners, it cannot typically be pursued, because of the physical distance from the trainee and the social constraints. Trainees may become annoyed or embarrassed by a hand on their shoulder for cultural and social reasons, e.g. being in front of the whole class. As MG2 stated:

> *"You do not reassure somebody with rational reasoning. In every situation, when somebody is afraid you touch them, hug them. Of course, there are different ways according to different contexts, but anyhow that's what we need [when we are afraid], and that's something that our culture is suspicious about because touching is allowed only in intimate relationships."*

Figure 7. A climbing instructor giving suggestions to a trainee.

Therefore, the instructor's communications to fearful trainees take place only verbally. However, the guides report two key problems regarding this kind of communication with the climbers. One difficulty is communicating at a distance, since both climbers and instructors have to shout at each other to be heard:

> *"When the climber is a bit stressed, those on the ground start shouting at her/him 'put your foot there!', but which foot? There where? (...) and then I have to shout and that's terrible, and then inevitably the belayer starts to shout because s/he wants to contribute too"* (MG2)

The other is the potential misunderstandings caused by the lack of a shared vocabulary. Often trainees do not immediately comprehend what the guide is trying to suggest to them, either because they do not know specific climbing terms or the meanings that certain common phrases have in the climbing context, e.g. 'leaning back' for getting ready to be lowered.

3.3.3.3 Trust

In climbing, there is an issue of objective danger and safety procedures, and an issue of subjective perception of danger and safety that might be referred to as perceived risk and trust. From the interviews with trainees, it emerged that in moments of difficulty their willingness to take a risk depends on their level of self-confidence ("*if you think you will make it, you make it; otherwise no*" - T11), confidence in the equipment ("*with the rope and a mattress on the ground, I feel safe*" - T9), and confidence in the partner ("*you need to tell yourself 'I know s/he is holding me', you need to trust the belayer and do not panic*" - T8). These three levels of confidence are commonly regarded as distinct, but they can be condensed into two levels, because the gear is always managed either by the climber or by the belayer. As MG4 said:

> *"The gear is handled by people. Thus, the trust in the gear depends on who is holding you. For example, they could have misplaced the rope in the Grigri or, conversely, you can trust them so much that you push yourself to the limits and put your climbing shoes even on tiny footholds".*

From these insights, it emerges that the belayer is the main guarantor of safety and the recipient of the trust on which the action is based.

However, the role of the belayer is not confined to managing the rope promptly and properly; s/he must be an active observer who makes the climber feel her/his presence constantly by supporting the climber’s actions and encouraging her/him. Indeed, when engaged in ascent, climbers need to know that they can rely on the belayers’ support (“*at the beginning you feel insecure and you have to tell yourself ‘no, I know that s/he is holding me’, I can trust*” - T1). Trust is therefore a fundamental aspect of the relationship between climber and belayer since it allows the climber to feel safe when moving out of her/his comfort zone and ultimately to perform the ascent successfully. When climbers do not trust the belayer completely, from time to time, they check on the belayer's attention.

> *“It’s annoying when, while belaying, people look around and not at me... I’m not saying that they should always look at me, but I need to know that I’m safe, that they will notice if I fall and that they will try to do something”* (T8).

Thus, in addition to correctly handling the rope, it is fundamental for the belayer to learn how to inspire the climber's trust by communicating presence and attention.

The trainees interviewed were very conscious of the responsibility of belaying (“*I’m even more stressed when I belay!*”- T10; “*Personally, I feel a lot the responsibility (...), just for the idea that you have the life of someone else in your hands*” - T5). Another interesting finding was that the belayer’s emotional state is often a reflection of the climber’s one, revealing a sense of empathy which often remains unspoken. The emotions are shared both in negative and positive moments, for example, as T5 expressed, keeping the rope in tension “*surely requires focus, and sometimes it is also scary because when one is in trouble there is at least stress*”, or, as others reported, lowering the climber off evokes satisfaction in the successful climb “*I’m enthusiastic for her*” (T11), “*Satisfied for her, for her happiness*” (T2).

Coping strategies against mistrust. In the interviews, the guides told the researcher that they address the issue of trust between climbing partners through specific exercises and simulations. For instance, they organise fall tests to demonstrate the effectiveness of the safety gear and procedures, but also to make trainees understand the importance of the belayer, because, as one of the trainees affirmed “[it is just] *by falling that you realise that there is someone holding you*” (T10). Moreover, the guides propose exercises to let climbers experience the lack of control and their dependence on the belayers, and to train belayers to be precise when communicating, for example, by telling trainees to climb blindfold, relying only on the belayer’s instructions.

3.4 Climbers' Attitude towards Technology

To delineate a possible design space for wearables in climbing, it was deemed necessary to investigate the attitudes of this sport community towards the use of technology, as well as gaining an understanding of the sport's dynamics and the difficulties encountered by beginners. Because climbing is a relatively 'minimalist' sport, where equipment consists of items essential for safety, it was vital to explore how acceptable technology would be during climbing practices, and the characteristics that would make it more acceptable. For this purpose, focus groups were preferred to individual interviews because they can foster rich discussions among participants and are more likely to reveal participants' motivations for using or not using technologies (Goodman, Kuniavsky, & Moed, 2012).

3.4.1 Participants

Two focus groups were conducted, one with nine participants (three females; six males, age M= 35 years) and one with six participants (one female; five males, age M= 31 years). It was deemed necessary to have more than one focus group in order to minimise the negative effects of group interviewing such as groupthink, unbalanced expertise, or the predominance of people with a stronger personality (Berg & Lune, 2014; Goodman et al., 2012). In both cases, some participants were recruited among FBK researchers, the researcher's acquaintances and snowball method. To comply with the recruitment criterion, participants needed to be amateur climbers with enough expertise and understanding of the sport to be able to make a meta-reflection on it (years of practice M= 6; the highest grade climbed leading ranging from 4b to 7b[2]). Although the level of engagement with technology was not a recruitment criterion, participants were asked about it in the selection form. It emerged that two participants did not own a smartphone, but only an older type of mobile phone; four people used no apps related to climbing; nine people used weather forecast apps; and five people used mapping and geolocation apps and devices for finding routes when going outdoors.

3.4.2 Procedure: Focus Groups with Probes

Both focus groups took place in the premises of FBK, the first in one of the common gardens and the second in a meeting room due to bad weather conditions. In both focus groups, the discussion started with an open question about what makes a good climbing day. The goal

[2] French grading system ('Climbing Grades', n.d.)

of the first question was to put participants at ease and get acquainted, and for the researchers to gain an understanding of what climbers judge positive and important. Then the discussion on the use of technology during sport practice was introduced.

To facilitate the discussion, three devices designed for climbing were presented to the focus groups as probes around which to revolve the conversation. These had been selected by the researcher from a range of wearable or portable devices. The three probe items were: a commercial product (Figure 8a), a Bachelors dissertation prototype (*Dundee Degree Show*, 2011) (Figure 8b), and a research prototype (Ladha et al., 2013) (Figure 8c).

Figure 8. Pictures of the probes used during the focus groups.

The devices shown in Figure 8a and 9b are both designed to be attached to the harness and support the communication between climbing partners, but in different ways; the device in Figure 8a is a Bluetooth loudspeaker that can be used to convey voice communication, while the one in Figure 8b is a remote control that uses LEDs buttons to allow climbing partners to exchange simple visual messages. These two probes were used to investigate whether communication between partners is perceived as a significant problem by climbers, and what technological solution they would prefer and why. The third device (Figure 8c) is composed of two bracelets enhanced with accelerometers that are able to distinguish between moments of movement, rest, and muscle tremors during a climber's ascent, and a visual interface where the climber can visualise her/his performance. This probe was chosen to investigate climbers' ideas about 'self-improvement', i.e. their opinions on whether such measurements would be informative and useful to improve performance.

The probes were introduced separately. For each of them, a picture and a quick explanation about the purpose and the functioning of the device was provided. The discussion was then fostered by the facilitator asking the participants whether they thought the devices would be useful and whether they would bring them along when going climbing. Each focus group lasted on average 40 minutes; the discussions were audio-recorded and then transcribed. The transcript contents were analysed using Thematic Analysis (Braun & Clarke, 2006). In the following paragraph, the results of both focus groups are presented jointly. Participants' quotations are anonymised; each one is coded with the letter C (for 'climber') followed by a number between 1 and 15.

3.4.3 Findings

Values and concerns about technology. From the focus groups, it emerged that the elements constituting a 'good climbing day' vary depending on the kind of climbing practised. Sport climbing, whether it is practised indoors or outdoors, is heavily focused on performance, so a climbing day will be seen as positive when climbers succeed in accomplishing a difficult ascent; whereas on outdoor multipitch routes, the positive outcomes of a climbing day encompass environmental aspects as well, such as the beauty of the landscape and the weather.

> *"If climbing in a crag, I think the grade is important for most of the people, in a mountain multipitch what matters can be the type of rock, the type of movements required... the view counts as well, and if you have been all they long waiting because it was too cold or too hot"* (C9).

Other aspects that can influence satisfaction in outdoor climbing are safety ("*I'm happy when I manage to return home safe and sound*" C12), the realisation of projects that have required preparation and are invested with expectations:

> *"In my opinion, it depends on the expectations as well, meaning that if you have planned to climb that route months in advance, waited for the snow to melt, for the weather to be good... accomplishing it makes you feel much better than climbing something by chance"* (C2)

and the remoteness and the isolation of a place:

> *"I like even the time spent approaching to the wall, I don't mind spending two hours approaching with the ropes in my backpack and then maybe to climb a shorter route if it is far from busy roads; remoteness makes it looks like an adventure"* (C11).

In both focus groups, participants shared the idea that, whichever the type of climbing, they have a good day when they are satisfied with their own performance, i.e. when they thought they had climbed well, and when they had a good understanding with their partner. The sense of having climbed well might come from climbing a grade higher than usual, but it is mostly an internal feeling - it means being aware of having had a good climbing technique with fluent movements:

> *"not being afraid, making fluid movements, feeling in harmony"* (C9);

> *"the sensations you have while you climb, if you feel at ease that day, then it's fine. Otherwise, if you are nervous and you cannot go up on an easy route, then negativity spreads"* (C11).

Another crucial element is the climbing partner, who has to be not only skilled but also must share a similar climbing vision and have the right temperament:

> *"I think it's important to have a partner that is able to keep up the morale"* (C12);

> *"To me it's important whom I go with because climbing is a matter of trust. If I go with people that I don't know and have a very different temper from mine, more impetuous, aggressive in the way to tackle the rock… I see I react differently from usual"* (C8).

Regarding the use of technology in general, the participants expressed a range of opinions, although the majority of them showed a certain resistance to technology. Six participants out of 15 explicitly said they were not in favour of using technology during their outdoor activities, unless it was strictly related to safety. They regarded outdoor activities as occasions to be immersed in nature, free from technology and social constraints:

> *"I think this summer I switched off the smartphone every weekend"* (C14);

> *"Taking selfies takes off the feeling of being there, that day, on that mountain, alone"* (C4);

> *"I would use technology to let other people know that I'm alive, but not for sharing pictures on social networks; I'm there for myself, not for the others to know"* (C10).

Conversely, three out of 15 participants were not refusing technology a priori ("*I don't go to the mountains to get rid of technology; if one day I want to get rid of it, I can go cycling on the bike path and leave the smartphone at home*" - C1). The remaining six participants did not offer explicit opinions on the matter.

During their assessment of the two devices for enhancing communication between climbing partners (Figure 8a, 9b), the participants acknowledged that the devices addressed a relevant issue but offered limited solutions. Participants from both focus groups interpreted these devices as designed for the mountaineering context, where coordination and communication are more difficult because there is significant distance between partners (from 25 to 40 metres) and often they cannot see each other. Conversely, the training bracelets were interpreted as designed for competitive amateurs who train in group to help them get stronger rather than to enjoy the experience of climbing and who are therefore more interested in the measurement of performance ("*I think it's something for competitive men, those that compare themselves and say, 'you loser, yesterday you have done only* [few easy ascents]" - C9) than in the full experience ("*If I had to train and keep track of my progress for climbing, I would be bored to death*" - C14). However, even when just considering performance measurement, the bracelets were seen as inadequate since they do not frame the problems of training and self-improvement properly.

Overall, it emerged that the likelihood of climbers accepting portable/wearable technology is influenced by the sport culture, which articulates values related to one of the following three broad dimensions: (i) the climbers themselves, such as expertise, independence, self-efficacy, and flow; (ii) the climbing community, such as a sense of belonging and pride; or (iii) the natural environment in which climbing is practised, such as the pleasure of immersion in nature, safety, and adventure. These values influence climbers' ideas about the purposes, roles, and the aesthetics of wearable technology, thus affecting the likelihood of acceptance. In the following paragraphs, participants' concerns regarding the use of technology in climbing will be presented in relation to the values these concerns reflect.

Individual values: expertise and challenge with oneself. Seeing climbing as an outdoor sport that challenges physical and mental capabilities while immersed in a wild and natural environment, the climbers' main concern was about delegating key skills to technology. In such context, relying on technology is considered hazardous mainly for three reasons: the risk of making experienced climbers lazy, the risk of getting inexperienced climbers into situations they cannot handle, and the risk that the technology does not work when needed. These concerns were clearly stated by C12 when he said:

> *"in my experience, I have seen that people get all the fancy brand new technology, but then, when they find themselves on a glacier, in most of the cases their phone is out of battery, they don't have a map with them because they were relying on the GPS, and even if they had it, they wouldn't be able to*

> *read it. In the end, they are stuck. From my point of view, tech is surely useful, but you cannot rely on it too much".*

From this point of view, the devices for augmenting partners' communication were seen positively because they allow information exchange to promote better coordination, leaving the responsibility with the climbers to judge what to do, based on their expertise. Of the two devices, the LED tool was preferred to the Bluetooth speaker because it supports intentional communication between climbing partners in an open, flexible manner, allowing them to establish the meanings associated with the coloured LEDs, as they commonly do with the pulling of the rope.

When considering the bracelets, participants lingered on what 'self-improvement' meant for them. It emerged that 'improving' is a complex concept in climbing, which consists not only of mastering efficient movements but also of gaining increasing self-confidence and control over negative mental states. Consequently, to assess whether they are improving, climbers usually rely on their internal sensations:

> *"Climbing faster doesn't mean climbing better (...) Well, I realise when I climb well. Sometimes I climb, and I feel that I'm moving well, while other times you stay on the wall like a gecko that looks up and doesn't know what to do"* (C10).

These reflections help to convey why the bracelets were not highly regarded, because they measure only movements. Furthermore, the way the bracelets measure movements was criticised too; some participants pointed out that for a good climbing technique the use of feet is more important than the use of hands, therefore the bracelets should be placed on ankles, and sensors measuring muscular contraction would be more appropriate than accelerometers to inform about the quality of the performance.

Increased fluidity of movement is another kind of improvement in climbing skills, but to improve in this area means to be able to tackle greater self-challenges like climbing a higher grade, even to the temporary detriment of fluidity of movement ("*I see my improvements when I feel confident and I climb a higher grade... maybe the first time you climb a higher grade you are all shaking* [but it's still an improvement]" - C4). Given these issues, the self-tracking bracelet was found to be too passive. According to the participants, to really affect climbing performance positively, it would be better if the tracking was combined with real-time feedback to know what movement to adjust during the performance, or with some elements of gamification to sustain motivation for training:

> *"I like to train, but when I'm alone I'm lazy. Now I have an uncomfortable schedule so it's hard to find a partner (...) but if this device can motivate you, maybe through some gamification elements or immediate feedback, then I would like it"* (C15).

In this way, the bracelets would help the climber to set new goals to challenge him/herself with.

Community values: sense of belonging and pride. Participants feared the negative judgment of their climber friends if they adopted any of the devices proposed. Regarding the bracelets, they affirmed: "*my friends would tell me: what have you put on? You don't need it; leave it in your backpack!*" (C10), "*If you are the only one to use you will look like a fool*" (C15). Moreover, they criticised the aesthetics of both the communication devices, which they thought were bulky and ugly. In general, participants tended to think the devices were more suitable for beginners since they are still in the learning phase and have not yet developed their own strategies for improving their climbing style or communicating with their partner, e.g. "*A person that wants to start climbing and thinks to buy a walkie-talkie* [might consider this kind of devices]" (C14), "*Or a mountain guide with a client*" (C11). Moreover, beginners have no prejudices about what is appropriate and what is not, and they encounter fewer problems regarding social image or peer pressure, e.g.

> *"If you started climbing when this device didn't exist yet, it's more difficult to accept. While, if when you do a climbing course, the instructor proposes you this from the very beginning, then it is normal to have it together with the rope and the quickdraws"* (C15).

Environmental values: Safety and Adventure. When mountaineering, climbers need to find a trade-off between the quest for adventure into the wild and the need for safety. In such contexts, climbers' main concerns are safety and the limitations to equipment to bring due to logistic reasons (climbers need to carry all their gear, apparel and food in their backpacks). These concerns lead them to prioritise gear and tools over any other things. Gear is perceived as the most reliable thing, and climbers would not accept the burden of extra weight unless they had a strong perception of usefulness and benefit. Although the two devices for augmenting communication can contribute indirectly to safety (because they allow better coordination between climbing partners), their value was not sufficiently convincing. As C12 explained, "*I would bring it with me on a multipitch because it's there that it's useful, but on a mountain multipitch I would rather bring two more protections, I mean... between the two, I choose safety*". Another powerful concern related to safety was the level of reliability of technology. During the focus groups, participants asked many questions about the battery duration and the signal range of the devices; they discussed the robustness of both materials (plastic vs. metal) and components (e.g. LEDs were judged more resistant and waterproof than microphones), as well as the risk of accidental errors. In this regard, the specificity of a device, i.e. the fact that the device is designed for just one purpose, was preferred because the common perception is that specificity entails battery duration and ease of use.

The practicalities of outdoor adventure also prompted many concerns related to the product design and the interaction required by the two devices for the augmented communication. Both devices were criticised for their size and the need to be hung at the harness, which reduces their visibility and usability, and increases the probability of accidental interaction or damage ("*Once I destroyed my backpack while I was climbing in a chimney*[3]*, I think that with such device…* [it wouldn't be possible to climb in such place]" - C7). In both cases, participants would have preferred a wearable artefact, like a bracelet, or a device to be applied on the shoulder lace of the backpack. From the interaction point of view, the Bluetooth loudspeaker was judged not handy enough to be used in the mountaineering context because it requires speaking through a smartphone (with phone signal implications) and occupies the climber's hands, which need to be free. Conversely, the LED device was deemed more appropriate for the mountaineering context because of its ease of interaction and non-intrusiveness. Some participants were fascinated by the possibility of communicating in a silent mode, compared to the noisy channels of walkie-talkies ("*It would make sense to use something to communicate that is not noisy. I think this is the key element of this device*" - C14). On the other hand, the device was found to be perhaps too discreet and there was a risk of messages not being noticed. Therefore, a few participants suggested adding an audio or vibrotactile notification to make the change in the LED status more noticeable ("*I would prefer a vibration, I don't like the invasiveness of sound*" - C8). Finally, it was considered suitable only to convey simple messages for the usual communications and not in case of emergency, when a more detailed communication would be needed, and walkie-talkies are the best option.

Overall, what emerged from these focus groups is that there are multiple ways to conceptualise and practise climbing, which are related to the motivations behind the choice to practise it, i.e. whether people search for a physical, performative experience or a more

[3] See glossary.

holistic one. The values of this community of sportspeople influence the role that technology should have to support them. In the next section, a design space will be defined on the basis of outcomes across all the fieldwork studies.

3.5 Design Space

This fieldwork was aimed at understanding 'what is climbing'. The actors in the learning setting, i.e. instructors and trainees, were interviewed to better understand what this sport requires. More experienced climbers were interviewed to gain their points of view on the use of technology during their sport practice. Thanks to these initial explorations, it is possible to delineate a design space for wearable devices in climbing informed by the needs, values, and emotions of potential users.

From this fieldwork, it emerged that people who choose to practise climbing are in search of a sport that puts them in contact with nature. Through the unmediated relationship with the rock, climbers can choose the challenges to set to themselves and experience a total absorption in their activity and liberation of the mind arising out of the high level of focus required. As climbers become more proficient, they experience a sense of accomplishment and self-efficacy when they overcome those challenges, and a sense of adventurousness in exploring places accessible only to people who master the same skills. These motivations apply both to novice and experienced climbers. With the passing of time, such shared motivations become entrenched, shared values of the climbing community and are nurtured by conventions for practising the sport in a certain way. Nevertheless, these positive feelings can often be hampered, and somehow even made more precious, by the difficulties that climbing involves. There are precise movement skills to be acquired as well as balance and proprioception. There are also negative emotions to keep under control. In fact, from the fieldwork interviews it became clear that emotions are tightly intertwined with movements. Negative emotions are more likely to be experienced by climbers when they are actually climbing, due to fear of falling or not knowing how to proceed. These problems typically have two main causes: perceived personal abilities and the need to rely on the belayer. Trust and coordination between climbing partners are fundamental for a successful ascent. During climbing training courses, instructors help trainees to gain self-confidence and trust in their partner through exercises that promote first-hand bodily experiences, through the use of auxiliary artefacts. These exercises are designed to help the novice familiarise with the new sensations, reveal invisible mechanisms, develop awareness, and sharpen sensorial perception. Then, when the negative emotions begin to prevail, instructors talk to their trainees, but are impeded by problems of distance, noise, and sometimes wind if climbing outdoors.

These findings that there can be a potential design space for wearable devices in climbing. Wearable devices are small, flexible, unobtrusive devices that are applied in direct contact with the body. They are suitable for climbing because they would not interpose between the climber and the wall; rather, they would work as an enhancement of climbers, thus preserving the direct relationship they have with the rock. In this way, the sense of self-challenge and self-efficacy that is so important to the climbing experience is not affected. Moreover, wearable devices can contribute to satisfy climbers' need for adventure, since they can be used outdoors and indoors, for every kind of ascent.

In the following sections the design opportunities and the constraints that articulate the design space will be presented.

3.5.1 Design Opportunities

Reveal invisible body mechanisms. Regarding the learning of new movements, the fieldwork showed that a large part of instructors' work is teaching trainees to move vertically in efficient ways without losing balance. Motor schemes for climbing require awareness of the body mechanisms underpinning balance and finely-tuned proprioception to detect when the body is out of place. For example, it is difficult for beginners to be consciously aware that they are climbing using only the tip of the toe, on which leg the weight of the body rests, or of the changes in balance related to swing of the hips. These days, instructors use auxiliary artefacts such as additional ropes, wooden blocks, pendulum, gloves, etc. to help trainees to gain this awareness. These findings highlight an opportunity for the design of wearable technology that helps beginners to develop better proprioception and become aware of such 'invisible' mechanisms.

Embrace body and mind. The fieldwork has revealed that in climbing the learning of new motor skills and the management of negative emotions are closely intertwined. Some movements generate fear, and fear can make trainees perform some movements poorly or not at all. Therefore, difficulty in performing certain movements may also be a sign of a particular state of mind. These problems suggest an opportunity for the design of wearables to explore how to address both aspects – motor skill learning and emotional state - when supporting teaching or training.

From Fear to Flow. The research has found that climbers seek the positive emotions associated with self-efficacy, sense of liberation, and complete focus that this sport can potentially provide, but, prior to that, they need to overcome several negative emotions, such as tension, stress, anxiety, frustration, or fear. Indeed, as discussed by MacAloon et al. (1983), the feeling of flow comes with a certain level of experience, while for beginners it is something to strive for. Regarding the negative emotions in the learning phase, the guides interviewed reported that they address fear only when it occurs and when the intensity of the emotion is so high it blocks the climber; otherwise, it is considered an inherent part of the activity. The potentially valuable outcomes of negative emotions in sport are supported by the research literature. For example, Hanin (2007) highlights that negative emotions can sometimes help athletes to maintain focus and sustain effort, while Brymer and Schweitzer (2012) report that, to some extent, climbers even seek such negative emotions because without difficulties, there would be no satisfaction. These findings suggest the design of wearable devices aimed at supporting the communication for managing negative emotions when they occur with intensity and prevent climbers from progressing. In order to do this, the wearable devices should activate in real time, when the beginner is blocked, and should aim to help her/him calm down and continue the ascent. Therefore, the goal of the wearables should not be to eliminate negative emotions, because in doing so the device would distort the nature of the sport, but rather to intervene at critical moments and help trainees overcome barriers. Then, when climbers are back on the ground, they can reflect on and treasure those moments. In this way, they can learn from these experiences and progressively move from fear to flow.

Build trust. Confidence in the belayer's attention and readiness for action is fundamental for the climber's composure and performance. However, novice belayers might not be skilled yet at reading signals of stress in climbers and providing them with practical and mental support. Moreover, from the fieldwork it was apparent that belayers have feelings of empathy for the climbers that often remain unspoken, e.g. satisfaction in the successful ascent or tension in a moment of difficulty. Since the climber needs to 'feel' the belayer's presence and attention, giving the belayer a way to express their empathy might improve the climber's experience of the ascent. This suggests an opportunity for the design of wearable devices that provide climbing partners with a means of expressing themselves, so that they can share their emotional states and tune their joint actions.

Overcome distance and noise. Communication in climbing is at the heart of teaching and takes the form of explanations or directions during the practical activities. It is instrumental to the coordination between partners. The fieldwork identified the communicative acts exchanged between instructor and trainees, and between climbing partners when the latter are on the wall. All these communicative acts are meant to support the climber during her/his ascent, but in different ways; some aim to promote the correct execution of movements, while others aim to instil confidence and build trust. Moreover, some communicative acts are well-defined, while others are vaguer and can be conveyed through non-verbal behaviour (e.g. by handling the rope). To gain a clear understanding of the differences, the communicative acts were analysed and arranged in a diagram along two orthogonal dimensions: a continuum ranging between functionality and emotionality, and a continuum between abstraction and concreteness (Figure 9).

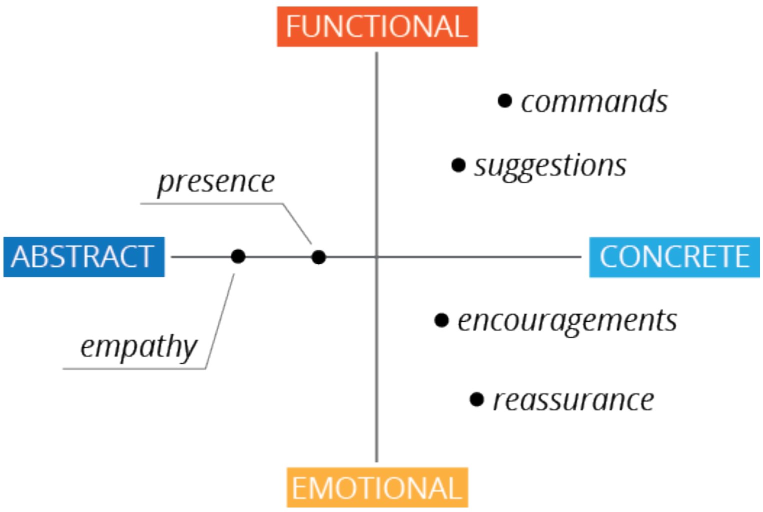


Figure 9. Different communicative acts in climbing.

The upper right quadrant is defined by the intersection of functional and concrete communication and includes commands and suggestions. Commands are meant to support coordination between the climbing partners and are often conveyed through conventional verbal expressions, while suggestions are verbal, defined messages typically seeking to help climbers reposition their body posture or indicate possible movements they had not yet considered. The lower right quadrant is defined by the intersection between concrete and emotional communication and includes encouragements and reassurance. Both these acts have an emotional function, but while reassurance is used when the climber's fear hinders her/his progression, encouragements work to reinforce the climber's self-confidence and can be used on many occasions, not only when fear strikes. The quadrants on the abstract side of the continuum includes the communicative acts conveying presence and empathy, which can have both functional and emotional purposes. Presence is the substrate of every communication (i.e. it is expressed every time somebody says something) and can help a climber perform a movement, as well as calm her/him down. Similarly, empathy can be emotional as well as kinaesthetic, the latter referring to people's innate body intelligence about where and when to perform an action in relation to other people (Fogtmann, Fritsch, & Kortbek, 2008), and can be useful to anticipate the climbers' needs. However, from our study it emerged that these communicative acts are not always effective due to environmental barriers such as distance and noise. The distance between the climber and the ground, the noise of gym settings, or the wind around outdoor cliffs can hamper mutual understanding between the actors involved. The partners usually shout their instructions, but this is a tiring and not always effective method. These issues suggest an opportunity for the design of wearable devices aimed at augmenting the existing communication between instructor and climber, and between belayer and climber. This goal is further supported by the fact that climbing is typically taught by qualified professionals, and that successful learning and performance arises out of successful communication, interpersonal understanding and trust between the actors involved.

3.5.2 Design Constraints

From the focus groups, it emerged that climbing is a sport discipline with its own culture. People climb not only to get fit and release tension, but also for the relationships they can establish with the environment, with fellow climbers, and with themselves.

Technology as a support, not as a substitute. During the focus groups, participants expressed reluctance towards technology that holds fundamental information for their trip and safety; they can accept to use technology, but they want to be sure that they can manage difficult situations without it. The value of self-efficacy, which consists in acquiring all the necessary competencies to tackle the challenges offered by natural elements, requires a technology that places itself as a support to, rather than a substitute of, climbers' abilities, and consequently help them to maintain an image of competence in front of the others.

Technology should be prompt, but not intrusive. The most gratifying state while climbing, and also the most researched, is that of flow. Flow is a state of engagement in activity that occurs when the activity presents the optimal level of difficulty to engage the climber without stressing her/him excessively. The importance of not interfering with the flow of an ascent is reflected in the climbers' preference for a technology that is prompt, timely, easily perceived and ready in case of need, but not intrusive.

Perceived usefulness. Climbing is a sport that makes use of minimalist equipment, both because the rock has to be tackled directly with the body and because climbers have to bring all the equipment on their shoulders when approaching the route. Therefore, a wearable object will be brought along only if its usefulness is actually recognised. For this reason, it is important that wearable technology has a well-defined purpose and is tailored to the needs and the context of climbing.

Reliability. Given the high risk involved in climbing, technology cannot afford to fail and mislead users in dangerous situations. It must be reliable both from a hardware and software point of view, e.g. batteries must last for a long time and the information it provides must be accurate.

Minimal encumbrance and handiness. Given the nature of climbing activity, which involves all of the body, and the outdoor context, which might be remote and arduous, a wearable device for climbers needs to be small, light, and offer simple and fast interaction.

3.6 Conclusion

Designing a wearable technology for an outdoor adventure sport raises great challenges about what kind of support the device should provide, and when and how it should intervene. From the fieldwork, it emerged that the learning difficulties experienced by beginner climbers are due to a high level of involvement of negative emotions such as discomfort and fear. The fear beginners experience mostly arises from the novelty of moving along a vertical wall and having to depend on another person for safety, which emphasise the importance of the relational dimension of this sport. So far, the instructors' techniques to overcome these difficulties involve artefacts that amplify the sensorial perceptions and help learners focus on the internal sensations and communication. More experienced climbers highlighted how technology for this sport should not contradict its values of cultivating expertise and self-challenge, being part of the climbing community, and search for adventure maintaining safety, which motivate people to practice this sport. The difficulties and emotions involved in climbing provide evidence for a possible design space, while the values inform the functional and product design requirements of a possible new wearable device for climbing. From these insights, a design space emerged which promotes the design of a wearable technology that works as a support for the body and the mind, acknowledging the importance of the actors involved and fostering the communication between them.

The next chapter will describe the co-design activities that have produced concepts of innovative wearable devices starting from the design space outlined here.

04 The Design Process

4. The Design Process

This chapter presents the activities of the Design Process, which explored possible technological solution to the design problem identified through the Fieldwork and led to the design of a wearable device for climbing.

4.1 Overview of the Design Process

Through the fieldwork, the design problem of wearable devices for climbers was identified in the types of support that these devices could provide for this outdoor sport. At the core of climbing performance is movement technique, which is strongly influenced by the climber's emotional state and her/his level of trust in the belayer, while the core value of the climbing community is the ability to successfully tackling the challenge of a route by putting into practice all the necessary expertise. Therefore, climbers would not delegate important information or their skills to a wearable device. The role of the device in supporting them should not be a *substitute* for the climber's skills, but rather a *facilitator* for actualising those skills whether in an expert or beginner. After defining the design problem and outlining the design space, the research proceeded via a co-design process aimed at conceiving new ideas for and building innovative wearable devices for sport climbing. In this research phase there have been moments of exploration and divergence, which have involved the participation of potential users and domain experts, and moments of convergence, where the researcher analysed the outcome of the explorations and made operational decisions. The design process involved three stages (for a general view of the organisation of the design process, see Table 3).

Study	Dates	Venues	N. of participants
Workshop 1: Exploring the design space	October 2015	Brainstorming room at the Interaction Lab of the University of Trento	8
Technological exploration	October – January 2016	FBK	The researcher
Workshop 2: Co-designing wearables for augmented communication	January 2016	Sanbapòlis climbing gym (Trento) + FBK open space	8

Table 3. Timeline of the Design Process.

A first co- design workshop took place in October 2015 and involved eight designers with personal knowledge of outdoor sports. This workshop was hold in the brainstorming room at the Interaction Lab of the University of Trento. Then, the researcher conducted a technological exploration to verify how to implement the results emerged from the workshop. Finally, a second co-design workshop was conducted involving eight between climbers and designers to further elaborate the concepts for a wearable device supporting climbing. This last workshop was conducted in January 2016 and took place both in the premises of a climbing gym and FBK. In the next section, each activity of the Design process will be presented in detail.

4.2 Exploring the Design Space

According to the fieldwork results, climbers are generally reluctant to use technology in their sport practice, albeit more positively inclined towards wearables. In particular, the participants recognised the potential usefulness of wearable technology for beginners, who need more support during the activity and might have fewer prejudices about technology since they do not yet have a personal vision of the sport practice. In keeping with these results, a design workshop was organised to explore what kind of wearable devices could support beginner climbers in their sport activity as well as *how* they could support them. The expected outcome of this workshop was a series of design concepts for innovative wearables.

4.2.1 Participants

Eight participants (three females, five males, age M= 35 years) took part in the workshop. Of these, seven were designers with experience of creative brainstorming and one participant was the CEO of a company developing technology for mountain sports. Among the seven designers, three were climbers and four had experience of mountain activities (such as via ferrata, hiking, etc.).

4.2.2 Procedure: Explorative Co-Design Workshop

The workshop took place in a room of the University of Trento designated for brainstorming sessions and lasted three hours. The first half hour was dedicated to participant introductions to help them get acquainted. In the next half hour, the facilitator explained to the participants how rock-climbing works, using illustrative slides and by showing the group the essential gear used in the sport, i.e. harness, rope, quickdraws, etc. (see Figure 10, on the left). The climbing gear was distributed among the participants so that it might act as a tangible stimulus which participants could inspect and touch. Following this, the facilitator outlined the main problems experienced by beginner climbers which had emerged in the fieldwork, namely:

- Developing proprioception;
- Performing climbing movements properly;
- Overcoming negative emotions and acquiring self-confidence;
- Trusting the belayer;
- Coordinating with her/him in joint actions (like managing the rope) at a distance.

These problems were presented as design opportunities, while the values emerged in the focus groups were presented as constraints for the creative and technological exploration in this workshop.

Figure 10. The explorative design workshop.

The creative activity lasted 90 minutes and it was set at a rapid pace where five minutes of production alternated with four minutes of feedback. This brisk rhythm was chosen with the aim of helping participants to speak out their ideas without being held back by any mental filters or brakes and focusing primarily on the feasibility of the ideas. Participants brainstormed first individually and then in pairs (for a more detailed description of the alternation of idea production and feedback segments and the individual and paired work, see Table 4.)

Protocol of the Exploratory Design Workshop
1. Produce some ideas individually (5 min). 2. Present your ideas to the person sitting next to you and exchange feedback (2+2 min). 3. Choose an idea among those you proposed, implement the feedback, and take it to the next level (5 min). 4. Show the result to the person sitting next to you and exchange feedback (2+2 min). 5. Pick up one of the ideas you exchanged feedback about, and work in pairs on it (5 min). 6. Present the idea to the couple sitting next to you and exchange feedback (2+2 min). 7. Exchange ideas and work in pairs on the idea you got and take it to the next level (5 min). 8. Present your work to the whole group, receiving feedback from everyone.

Table 4. Protocol of the Exploratory design workshop.

Participants were put in pairs by the facilitator so that members were not too familiar with one another and their competencies were balanced. The facilitator provided a description of the design opportunities in a written format, each one on a separate sheet of paper. Participants were asked to read them, pick one up, and brainstorm ideas for it by sketching a design concept. Sketches were preferred to notes on post-its since sketches typically allow presenting detailed ideas more quickly, where form-related factors and interaction details can readily emerge. During the activity, pictures and notes were taken by the facilitator, and the final presentations of the ideas and the feedback were audio-recorded so that the researcher could later reflect on and understand the motivations behind participants' choices. The sketches were also collected at the end of the workshop.

4.2.3 Findings

The concepts produced were analysed on the basis of the problem addressed and the solution offered in terms of technology, actors, interaction modalities, content of the communicative exchange, and sensorial channels involved. Three out of the four concepts produced reflected the importance of the relationship between the climbing partners and took into consideration the emotional involvement of climbers, while the fourth one addressed the design opportunity of learning to perform climbing movements properly. Each of the concepts produced is summarised in Table 5.

The concepts produced during this workshop enable an initial mapping of the design space of wearable devices for climbing. As the purpose, it emerged that wearables could be deployed to create greater awareness of the sometimes invisible physical and psychological mechanisms entailed by climbing, such as balance, fear, and attention. In the concepts produced, wearables were used to enable the actors involved either to perceive these invisible mechanisms, as in the sonification concept where they informed about the shift of the climber's weight, or to express those mechanisms, as in the augmented T-shirt concept where they were used to inform about the climber's mood. Uncovering the invisible mechanisms is primarily a way to enable the belayer to intervene in support of the climber through the communication of her/his presence or suggestions. The communication of these messages occurred through feedback which was deployed and characterised in different ways in the concepts produced. Feedback was either generated automatically by the technology or it was sent by the belayer, and it was used to express both functional and emotional messages. However, across all of the concepts, feedback had a common feature: when used in real time, it had to convey simple messages and via a subtle modality in order to avoid surprise and cognitive overload for the climber.

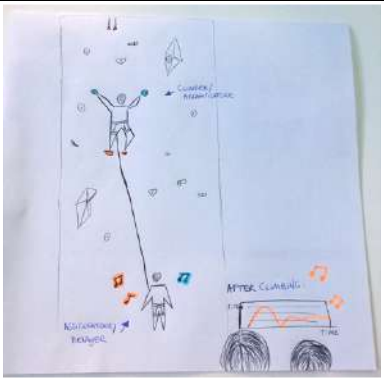
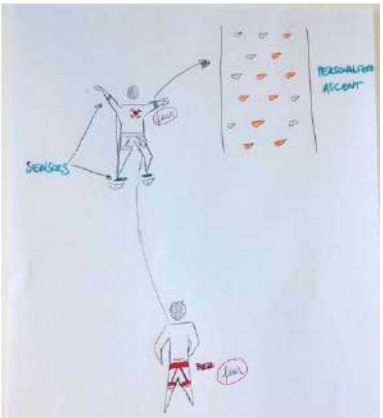
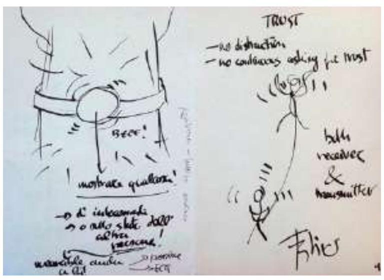
<table>
<tr><td colspan="2">Sonification of performance</td></tr>
<tr><td>
</td><td>This concept addresses the issue of learning the proper climbing technique, and specifically to learn to use legs rather than arms during the ascent (a typical mistake of beginners is pulling themselves up with arms rather than pushing with their legs). While the climber moves up, s/he triggers music that changes according to the pressure s/he applies on the holds. The music is heard by the belayer in real time so that s/he can get a preliminary idea of what the ascent requires. The music is also recorded so that the climbing partners can listen and reflect on it together after the performance.</td></tr>
<tr><td colspan="2">Emotional communication through augmented T-shirt</td></tr>
<tr><td>
</td><td>This concept envisages a solution to the problem of how to reassure the climber when s/he is stressed or afraid and thus risks performing incorrect movements. The climber wears a T-shirt enhanced with Galvanic Skin Response and heart rate sensors, and pressure and heat actuators. On the other side, the belayer wears a similar T-shirt that helps her/him feel the emotions felt by the climber, thus fostering feelings of empathy. When the sensors detect that the climber is scared, the belayer can make the actuators in the climber's T-shirt react correspondingly simulating a hug.</td></tr>
<tr><td colspan="2">Personalised training and notification of fear</td></tr>
<tr><td>
</td><td>This concept tries to tackle both the problem of how to improve performance and how to manage negative emotions. By using the data captured from sensors placed on the four limbs, the system is able to track the climber's performance and to give her/him feedback through a visualisation system at the end of the ascent. The data from the performance can be used to create personalised ascents for training. Moreover, in critical moments, sensors capture data about the climber's emotional state and communicate it to the belayer through a vibration mechanism on the harness.</td></tr>
<tr><td colspan="2">Monitoring the belayer's attention to foster trust</td></tr>
<tr><td>
</td><td>This concept tries to address a common problem among beginners, which is the fear that the belayer does not pay sufficient attention to her/him. This concept proposes a solution were the belayer has to demonstrate her/his attention. In particular, while the climber moves up the wall, the belayer has to look at something every few seconds to prove that she is attentive and engaged in her task. The object on the wall can detect the belayer's glance through a camera. If she does not look at it, she receives a vibration on her harness. The climber receives no feedback about the belayer's attention, but s/he knows s/he can rely on the system.</td></tr>
</table>

Table 5. Concepts emerged from the Contextual Co-Design Workshop.

The participants judged the visual and auditory modalities to be inappropriate for real-time feedback in this context, given that the attention of both climbing partners should be dedicated to the activity. Furthermore, the auditory channel cannot be isolated because it is used for exchanging instructions and monitoring the environment. Consequently, haptics emerged as the participants' preferred modality and was selected as feedback for three concepts because it is a non-invasive form of communication and can easily be embedded in the gear and apparel already used in climbing and it fully exploit the characteristic of wearables of being in contact with the skin.

Overall, the explorative workshop shed light on how wearables can support climbing. Specifically, it emerged that real-time feedback about the actor's physical and psychological state is important both to increase climbers and belayers' awareness of a situation and help them intervene to improve it. Moreover, haptic sensations, such as vibration, heat, and pressure emerged as the preferred feedback modality. Consequently, an exploration of the different types of haptic feedback and the technologies able to provide it was conducted. The results of this exploration are reported in the next section.

4.3 Technological Exploration

The goal of this research phase was to gain a detailed understanding of the characteristics and the potentialities of feedback in general, and haptic feedback specifically. The ultimate goal was to understand how to apply haptic feedback to the case study of climbing and get an overview of the available technology to embed this feedback in a wearable device. Therefore, this section presents a literature review describing the different types and uses of feedback in sports and the nature of haptic feedback and its use in HCI, and a comparison of different actuators for tactile sensations.

4.3.1 Feedback in Sports

While learning a sport, trainees progressively improve by trial and error (Lauber & Keller, 2012). To gauge whether they are performing well, they rely on indicators such as achievement of goals, inherent (or intrinsic) feedback, or augmented (or extrinsic) feedback. *Inherent* feedback is the information originating from the trainee's perception of her/his own movements and position in space (i.e. proprioception), while *augmented* feedback is the information coming from an external agent (Schmidt & Lee, 2011), such as the coach's verbal indications or qualitative video-based motion analysis (Phillips, Farrow, Ball, & Helmer, 2013)[4]. Beginner athletes in particular need feedback because during the performance their focus of attention may be devoted to the many aspects of the activity, such as the next movement required, the physical effort, and control over emotional state, rather than on the accuracy of their current movements. For example, people learning to ski often fall without understanding the nature of their mistake. They perform an exercise thinking they have their limbs properly aligned, and it is only after receiving trainer feedback that they can re-assess their proprioceptive sensations, adjust their posture, and internalise the sensations generated by the new, correct position. Therefore, the extrinsic feedback works as a yardstick for the inherent feedback (Schmidt & Lee, 2011) and help beginners to re-focus on their internal sensation and to better understand the mechanism of their performance.

Augmented feedback can be categorised according to the content it expresses and the timing of delivery. It can express a Knowledge of Performance (KP) when it refers to the quality of movements, or Knowledge of Results (KR) when it refers to the goal/level achieved. Moreover, feedback can be *concurrent* if sent while executing the movement (i.e. in real time) or *terminal* if sent once the movement has concluded (Young, Schmidt, & Lee, 1991). According to Thorndike (1927; in (van Erp, Saturday, & Jansen, 2006) the success of sport training depends on four attributes of the augmented feedback, namely i) frequency; ii) accuracy; iii) timeliness; iv) information richness. To be truly effective, these four attributes have to be combined with the different categories of feedback and adapted to the tasks required by the specific sport. For example, concurrent feedback conveying knowledge of performance is more appropriate to minimise errors in continuous tasks (Young et al., 1991) such as in sports requiring the acquisition of special movements, as in golf or skiing, or where good performance lies in the quality of the movements, as in gymnastics, board sports (skateboarding, snowboarding, surfing), dancing and climbing.

Thorndike's attributes for effective sport training do not necessarily mean that *more* feedback is always the best solution. On the contrary, excessive feedback may bring several disadvantages. For example, one possible drawback of information richness is cognitive overload. With concurrent feedback for knowledge of performance, athletes must be able to perceive, interpret, and react to the feedback while they are performing another activity as the primary task. For this reason, the feedback complexity and salience must be calibrated on the complexity of the task (Phillips et al., 2013; Sigrist, Rauter, Riener, & Wolf, 2013).

[4] Henceforth, unless explicitly stated differently, in this manuscript the generic term *feedback* will refer to the extrinsic/augmented feedback.

Other possible drawbacks relate to the frequency of the feedback: *passive learning*, i.e. the trainee does not actively perform the exercise but waits to be guided; and *feedback dependence*, i.e. the inability to perform an exercise autonomously without the feedback (Schmidt & Lee, 2011). According to Feygin et al. (2002), these issues can be overcome with a training plan that envisages the gradual elimination of the feedback. Indeed, there is a defined moment in the sport's learning curve when it is more appropriate to provide feedback. The learning of motor skills can be divided into three stages: cognitive, associative, and autonomous (Mononen, 2007). In the cognitive stage, the trainer explains to the trainees how to execute a specific exercise and the trainee tries to understand what is required; in the associative stage, the trainee tries to match the correct movement with her/his internal sensations, and progressively improves by trial and error; finally, in the autonomous stage, the trainee is supposed to have internalised the right movements and no longer needs guidance. Indeed, the frequency of feedback should decrease as the skill level of the trainee increases (Sigrist et al., 2013). In addition to the gradual removal of feedback, van der Linden et al. (2011) suggest shifting the control of the feedback to the users, leveraging on their sense of responsibility.

Similarly, problems arise when it is not possible to convey adequate feedback because of environmental barriers such as distance between instructor and trainee, noise, or group management factors. In sports like skiing, surfing, or climbing, the physical distance between trainer and trainee may restrict vision and hinder or prevent the usual teaching techniques, such as imitation and direct modification of the body posture. In other cases, noisy environments (such as gyms for climbing or dancing halls) may inhibit direct voice instructions. Furthermore, it is rare to have personal training; normally a trainer must work with a group of people, hence her/his feedback to specific individuals can be less frequent and accurate than is optimal. In all these cases, technology has been developed to support trainers to overcome the environmental obstacles.

HCI research for sport, although still a relatively new area, shows that augmented feedback has been investigated mainly in terms of perceptibility, understanding and efficacy. Concurrent feedback for knowledge of performance is the type most commonly investigated. In the literature, this feedback has usually been conveyed through subtle modalities such as LED lights, sounds, and vibrations. Some studies have investigated the effects of real time feedback in one modality on a specific sport, e.g. sonification for skiers (Hasegawa et al., 2012), vibration for rowers (van Erp et al., 2006), visual feedback in group cycling (Walmink et al., 2014). Other studies compared the three modalities in order to assess which was the most salient and recognisable without disturbing or overloading cognitively the athletes in a specific sport. Bächlin et al. (2009) compared audio, visual, and tactile feedback for the training of swimmers and showed that audio is the modality that performed worst, eliciting the longest reaction times by the athletes. Similarly, Kosmalla et al. (2016) compared the three modalities in a climbing setting and showed that the visual modality performed worst. These two studies show that the suitability of augmented feedback is strongly influenced by the nature of the sport and by the environment in which it is performed. Finally, other studies have investigated the effectiveness of multimodal feedback: Nakamura et al. (2005) presented a system that combines video with vibration cues to learn how to dance.

The next section will focus on haptic feedback and its use in HCI for the sports domain.

4.3.2 Haptic Feedback in HCI

Haptic is an umbrella term that covers the sensations provided by the sense of touch and the body in movement. The perceptions arising from the sense of touch can be both functional (e.g. informing about the temperature of a room or about the weight of an object) and emotional (e.g. informing about the emotional state of a person who leaves a room slamming the door). Moreover, touch has a special relational function; being local, in direct contact with the body, and private, it is the preferred sensorial modality to express interpersonal closeness and intimacy (Durlach and Slater, 2000; in (Basdogan, Ho, Srinivasan, & Slater, 2000). According to the classification proposed by Oakley et al. (2000), the different kind of haptic perceptions can be categorised as follows (see Figure 11):

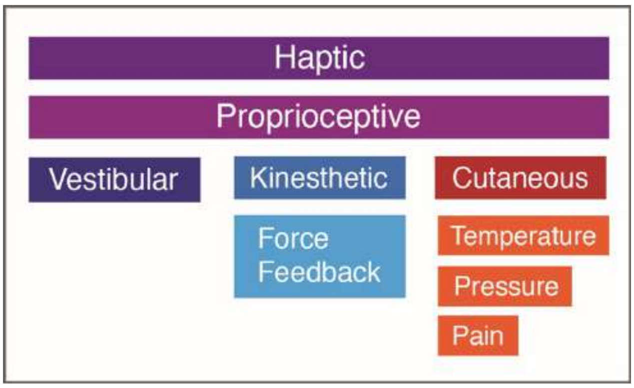


Figure 11. Sub-categories of haptic perception

- *Haptic,* which is used to identify the sensations derived from the sense of touch in general and includes all the following terms.

- *Proprioceptive,* which includes the information provided by the cutaneous, kinaesthetic, and vestibular sensations and refers to the awareness of the position, state and movement of the body and limbs in space.
- *Vestibular* perception concerns balance, the position of the head, acceleration and deceleration during movements. These perceptions are considered part of touch even though they arise from sensations generated by the inner ear.
- *Kinaesthetic* perception refers to the feeling of motion; it relates to the sensations originating in muscles, tendons, and joints, whereas *force feedback* specifically relates to information about mechanical forces sensed by the human kinaesthetic system.
- *Cutaneous* perception pertains to the skin as a sense organ and includes the sensations of pressure, temperature and pain. The lips, the hands and the soles of the feet are the most sensitive parts of the body for cutaneous perception (Hale & Stanney, 2004), but it is possible to get these sensations to different degrees from all over the body. The term *tactile* refers to the cutaneous sense, but more specifically to the sensation of pressure rather than temperature or pain.

Due to the human capacity to gather sensorial impressions both from static body situations (cutaneous perception) and dynamic body situations (kinaesthetic perception), people rely on their sense of touch (along with other modalities) to explore the world that surrounds them and to regulate their intentional movements in space. As Carbon and Jakesch (2013) pointed out, the sense of touch has the particularity of being *responsive and reflective* at the same time, which means that when a person touches a thing, that person also perceives herself as being touched *by* that thing. Gibson (1962; in (Carbon & Jakesch, 2013) classified this condition of mutual influence between the person who touches and the touched entity as *active* and *passive* touch. Touch is considered active when a person actively brings the tactile impression on her/his skin, and passive when it refers to the feeling of being touched, i.e. when the tactile impression is induced by an external object. Due to this characteristic, touch is said to be an interactive sense and can be considered a "*sensorial mode that integrates our experience of the world with that of ourselves*" (Motamedi, 2007).

Although not yet widely explored, the properties of passive touch in the interaction with technology via implementation of haptic feedback have been investigated in some HCI studies. So far, haptic feedback has been deployed mostly in the domains of Feedback, Augmented Communication and Motor Skills Learning. As a feedback, it has been deployed to give confirmation of touchscreen interactions on mobile devices (S. Brewster, Chohan, &

Brown, 2007). As a way to augment communication in remote interpersonal interactions, haptic feedback has been deployed to encode and convey abstract meanings through tactile icons called 'Tactons' (S. A. Brewster & Brown, 2004) or to put in contact people and help them convey emotions and prosodic communication through the so-called 'mediated social touch' (Brave & Dahley, 1997; Väänänen-Vainio-Mattila, Häkkilä, Karukka, & Kytökorpi, 2012; Huisman, Darriba Frederiks, Van Dijk, Hevlen, & Krose, 2013), or to give people the sense of being co-located in collaborative virtual environments (Basdogan et al., 2000; Sallnäs, Rassmus-Gröhn, & Sjöström, 2000). A specific field where the potential of haptic feedback to convey authenticity in interpersonal interactions has been explored is Human-Robot Interaction. In the work of (Marti, 2010), the emotional state of an animal-like robot was conveyed by changes in its fur, i.e. using visual and tactile modes to provide a more authentic reaction and engaging interaction.

In the field of Motor Skills Learning, haptic feedback has been investigated as a way to support people to perform certain movements. Some studies have investigated the acquisition of motor skills by providing people with a kinaesthetic understanding of the required movement via a desktop device that provides force feedback and is moved through a stylus, like the PHANTOM® (Feygin et al., 2002). This desktop technology for haptic feedback has been applied extensively in the medical sector. Thanks to its capacity to simulate the consistency and texture of tissues and organs, force feedback was used to train apprentice surgeons to operate (Wagner, Stylopoulos, & Howe, 2002), (Morris, Hong, Barbagli, Chang, & Salisbury, 2007). Other studies investigating Motor Skills Learning explored the potential of wearable actuators, which allow a greater freedom of movement and the use of parts of the body other than hands. Lieberman and Breazeal (2007) developed a haptic suit enhanced with vibrotactile actuators for haptic guidance, i.e. using haptic stimuli to guide the person through the ideal motion (Feygin et al., 2002). The vibrotactile feedback was used to signal errors in the trajectory of the gesture, and hence keep the user on the right trajectory. A similar wearable haptic system has been developed for teaching violin (Van Der Linden et al., 2011).

As already mentioned in the Related Work chapter, haptic feedback has also been investigated specifically in the field of sports, where it has been deployed both for motor learning (or improving) and augmented communication purposes. For motor skills acquisition, it has been used to convey knowledge of results - for example, it has been deployed by (van Erp et al., 2006) to notify athletes of their achievements, by placing vibrating motors on rowers' bodies and programming them to vibrate simultaneously when movements of the upper and lower limbs were coordinated. As knowledge of performance, haptic feedback has been adopted to signal errors in the position of climbers' feet, by placing a vibrating motor on each shoe and sending two different vibrations to signal two different kinds of errors (Feeken et al., 2016). Similarly, it has been adopted to signal asymmetry in the movement of legs during running by applying a vibrating motor to each leg and pairing it to an accelerometer (Fiorentino, Uva, Foglia, & Bevilacqua, 2013). Conversely, (Stewart et al., 2014) have used haptic feedback to generate awareness of performance in roller derby skaters in a reflective way, i.e. by creating a vibration system whose rhythm reflected the speed of performance: the faster the skater's performance, the faster the pulse and vice versa. Some other studies have used vibration as *feedforward* rather than feedback, i.e. as an instruction that precedes the action. Along these lines, Bial et al. (2011) have employed different kinds of vibration to suggest cyclists when and how change gear and different rhythms to suggest the pedalling pace. In the context of snowboarding, Spelmezan (2012) placed two vibration motors on the shoulders and the thighs of snowboarders and made them vibrate sequentially to suggest the direction to turn. Similarly, Aggravi et al. (2016) have used vibration to indicate to blind skiers when to turn. However, in this last case, the vibration was manually activated by the instructor pressing a button rather than automatically triggered by accelerators. Indeed, in sports which due to their nature require a spatial distance between the instructor and trainee, often researchers have chosen to use haptic feedback to put the two actors in direct contact, thus intertwining the functions of haptic feedback to augment communication and to enhance motor learning. A similar concept was developed by (Schmid et al., 2015) for kiteboarding. The authors embedded the vibration in the steering bar of a kiteboard novice and made it vibrate in response of the movements of the instructor's bar, creating a shared object model between the instructor's and the trainee's bars. Finally, examples of haptic feedback for Augmented Communication in remote sport interactions can be found in the work of Woźniak et al. (2015) and Curmi et al. (2017) who deployed vibration to make runners perceive the single cheers of remote audience members in real time.

This literature review has shown that haptic feedback is a compelling option for real-time feedback through wearable devices since it exploits their key characteristic of being in direct contact with the body. By touching the skin, wearable devices can provide cutaneous feedback (such as pressure, heat, or vibration) which is private and immediate because its perception cannot be avoided by the wearer. In the domain of wearables for sport, haptic feedback has the advantage of not requiring visual attention, so that athletes can stay focused on their main activity. Moreover, unlike other types of feedback widely used in sports, such as video recordings of the performance, apps on mobile, etc., haptic feedback is positional, i.e. it can be applied to the parts of the body involved in a specific movement and convey suggestions about how to move those parts of the body specifically. Therefore, haptic feedback can be a way to enhance athletes' awareness of their bodily states (proprioception) through cutaneous perception. Notably, in all the cases, analysed vibration was the preferred sub-modality of haptic feedback. Thanks to its ease of modulation, different meanings can be encoded with different levels of complexity of content and expression. For example, Bial et al. (2011) modulated the vibration of a single motor and were able to communicate to cyclists when to change gear (and whether to increase it or decrease it) and what pace of pedalling to sustain.

In climbing, the sense of touch is fundamental, and climbers are already sensitised and alert to it. By tackling the wall with bare hands, climbers explore the materiality of the rock in a tactile way, in search of the best holds, and, through the spatial sensations of touch like kinesthesis and proprioception, they perceive the inclination of the wall and adjust their balance accordingly (Dutkiewicz, 2014). Given that touch as an information channel is already open in climbing, haptic feedback might be an appropriate way to provide climbers with knowledge about their performance. Moreover, haptic feedback is demonstrably readily perceived while climbing (Kosmalla et al., 2016). Non-verbal communication through touch is already partially used by climbing partners for coordination and reassurance. They communicate their needs to each other by pulling the rope and the belayer communicates her/his presence to the climber by keeping the rope tensed. During the fieldwork, one guide affirmed that when reassurance is needed, it would be of great help to touch the fearful climber, but this is not usually appropriate due to social norms. In cases like this, mediated social touch is a solution worth exploring, as a way to mimic interpersonal touch, like a pat on the back. Indeed, haptic feedback has been demonstrated to be a privileged channel for interpersonal, non-verbal communication, especially to convey information about presence, closeness and emotional states.

In conclusion, this review has shown that the studies published so far in the literature on the use of haptic feedback for motor skills acquisition have focused almost exclusively on vibrotactile feedback. Nevertheless, for the research process presented in this thesis, different types of tactile feedback were explored and compared in order to determine the most appropriate haptic sub-modality for real-time feedback in the context of climbing. In the next section, the results of the comparison will be presented.

4.3.3 Comparing Different Actuators for Tactile Feedback

In light of the workshop results indicating a preference for tactile feedback, and the literature review which revealed the communicative potential and versatility of haptic feedback in sports, a range of actuators of tactile sensations was investigated. Four types of actuators, providing different forms of cutaneous feedback, were purchased, namely: i) a heating pad and ii) a thermoelectric cooler, both for thermal sensations, iii) muscle wires for pressure sensations, and iv) vibration motors for cutaneous stimulation through vibration. (For a detailed description of the actuators, see Table 6).

The tests and comparisons of the actuators were conducted together with the Energy Efficient Embedded Digital Architecture (E3DA) research unit of Fondazione Bruno Kessler (FBK). In the end, vibrating motors were preferred to the other actuators due to their lower battery consumption and the ease of modulation. Indeed, with vibrating motors, it is possible to create different vibration sequences which are easy to perceive by varying the number of motors and the intensity, duration, and pauses of the vibration. Conversely, heating pads need a lot of energy and warm up relatively slowly (approximately two minutes), and there is a risk they are not perceived readily because of concurrent homeostasis, i.e. the natural adaptation of the body to the surrounding environment to maintain balance with it. Indeed, temperature is perceived by contrast in the first few moments following a change and then slowly the human body gets used to it. The high level of battery consumption and the slow reaction time made heating pads unsuitable for a context such as climbing, where fluent and continuous movements and sudden mood changes necessitate quick feedback. Thermoelectric coolers also require high energy consumption, and to work properly they need a heat sink which requires additional energy and would make the cooler too bulky and thus unsuitable for wearing on the body. The muscle wire was discounted because the material of which it was made was judged too fragile and it would have required an additional study to understand how to embed the wire in a protective shield in order to use it on a moving body without breaking or harming the wearer but at the same time, ensuring that it is easy to perceive.

On the basis of these results, a second workshop with both climbers and designers was organised to explore the possible uses of vibrotactile feedback to enhance real-time communication in the climbing context.

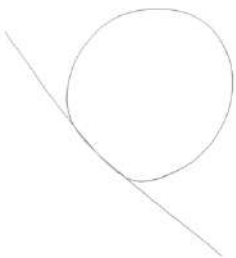
LilyPad Vibe Board 	A small (20mm outer diameter) but powerful vibration motor works well as a physical indicator. It has a thin (0.8mm) Power Circuit Breaker (PCB) and requires 5V power.
Heating Pad 	These heating pads are constructed using a mesh of Polyester filament and Micro Metal Conductive Fibre folded into a protective Polyimide Film. By applying 5V direct current to the wire leads, the pad will begin to warm up within few minutes, getting warm to the touch but not too hot. They are ideal for things like hand-warmers and other heated garments. Size: 5 x 15 cm; 5 x 10 cm.
Thermoelectric Cooler 	Thermoelectric coolers (TEC or Peltier) create a temperature differential on each side: one side gets hot, while the other side gets cool. Therefore, they can be used to either warm up or cool down something, depending on which side is used. Peltier work very well as long as the heat is removed from the hot side with a heat sink or other device; otherwise, the Peltier will quickly reach stasis and will not increase anymore the temperature on each side. Features: Size: 40 x 40 x 3.6 mm Max Operating Temperature: 180°C Min Operating Temperature: -50°C
Muscle Wire Actuator 	0.012" Muscle Wire® (or shape memory Nitinol) is a one-foot long piece of nickel-titanium alloy that can flex and contract when a specific amount of heat or current is applied to it. When the wire is at a low temperature, it is said to be in a *martensitic* form; when it is at a high temperature, it takes its *austenite* form. When the Muscle Wire® is in its martensitic form, it can be formed and bent into different shapes. Nevertheless, thanks to the shape memory, when an electrical current of ~1.5A is applied to the wire or it is heated to ~100°C, it reverts to the austenite form and recovers its previous shape with great force.

Table 6. Actuators compared.

4.4 Co-Designing Wearables for Augmented Communication

The first explorative design workshop provided strong directions concerning the purpose of technology, i.e. it should enhance the communication between climbing partners, and concerning the preferred modality of the technology, i.e. haptic feedback. Notwithstanding these directions, a few questions remained unanswered, for example where on the body it is preferable to wear such a device while climbing, and what kinds of messages should be conveyed, when they should be conveyed, and through which input. The goal of the second workshop was therefore to inform the design of a vibrotactile wearable device in terms of product, communication and interaction design. Furthermore, given that the importance of personal expertise and mutual trust between climbing partners emerged so clearly in the fieldwork, the workshop was focused on the ways to augment interpersonal communication between the actors, excluding any information provided by sensors.

4.4.1 Participants

Eight participants were involved (four females, four males, age *M*= 33 years):

- two mountaineering professionals (i.e. a mountain guide and a member of the Mountain Rescue Service);
- one amateur climber;
- three interaction designers (one of which was an amateur climber too);
- two people interested in learning how to climb.

The varying levels of mountaineering experience (from novice to professional) ensured that many points of views on climbing were potentially captured. Participation in the workshop was free of charge - the only benefits participants received were the paid entrance to the climbing gym, a lesson from a professional mountain guide, and lunch. Climbing gear was offered by the mountain guide to the participants who lacked it.

4.4.2 Procedure: Contextual Co-design Workshop

Knowledge of climbing is difficult to convey because it is mostly tacit and practice-based, i.e. comprised of tactile, auditory, and kinaesthetic sensations, as well as emotional and social dynamics which are also hard to articulate. Moreover, when designing wearables, representations such as renderings and visualisations cannot provide the same accuracy as felt experiences (Tomico & Wilde, 2015). Conversely, situated experiences and technological explorations allow for the emergence of embodied and collocated interactions. For these reasons, this workshop was organised as a co-design activity involving both climbers and designers and conducted in the premises of a climbing gym. This method was chosen to foster a process of mutual learning between people highly skilled in their own fields and to inspire them through bodily engagement with the context. The aim was, on the one hand, to put designers in climbers' shoes and involve them in a creative session where they could use their bodies to engage with real artefacts and to stage their concepts in the real context of use; and on the other hand, to encourage climbers to change their perspective on technology and be proactive and constructive rather than just critical. The workshop was divided into three main activities: i) climbing experience, ii) bodystorming, and iii) refinement of concepts. In the following paragraphs, each activity will be described in detail.

Climbing experience. The workshop started with a 90-minute climbing lesson led by the mountain guide (Figure 12). The idea behind this activity was to engage participants primarily at a physical level and to create a common ground of experience among them; it had to be primarily a sensorial experience. By embodying the climbing experience, the designers could gain awareness of the required movements and focus, the emotional involvement, and the coordination with the partner.

Figure 12. Contextual Co-design Workshop: the climbing session.

Meanwhile the climbers could experience the feeling of climbing with an inexperienced belayer supporting them. Climbing partners were also asked to work together in subsequent activities so that they could reflect together on the experience just concluded and draw ideas from it. Individuals were paired up by the facilitator in order to balance the participants' expertise in climbing and in creative workshops; the exception was the pairing of the mountain guide and his assistant, both climbing experts only.

Bodystorming. Once the climbing lesson was over, the group was invited to sit on the mattresses of the bouldering area and reflect on the experience (Figure 13). The facilitator prompted a discussion on communication in climbing by asking the participants if they exchanged any kind of communication with their partners or with the instructors in their short practice segment and, if so, to report their experience. Then the group discussed the problems encountered with voice communication in a climbing environment (both indoors and outdoors) and the possible benefits that augmented communication could bring. At this point, the facilitator explained the characteristics of vibration and made participants try different modulations of a string of vibrating motors in their hands (Figure 13, centre and right).

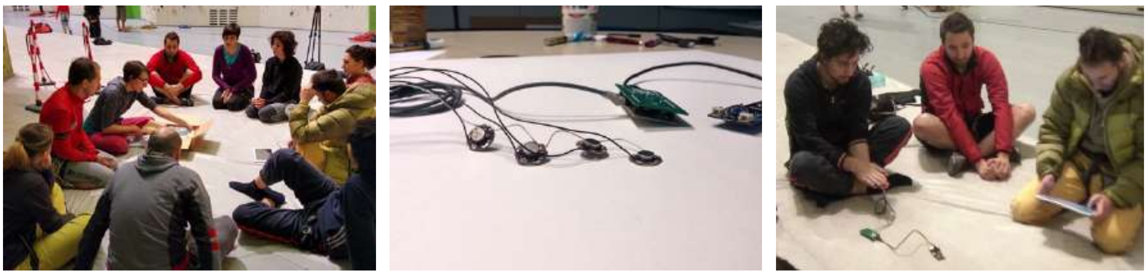


Figure 13. Introduction to the bodystorming phase.

After this introduction, the main bodystorming phase started. The participants were asked to conceive a wearable device for augmented communication through vibration. The kind of communication was not specified; the wearable could be used to convey instructions to the climber about how to move, to make the climber feel safer, to improve the partners' coordination in joint actions, etc. Being situated in the bouldering area where the holds are low and there are mattresses on the floor, participants could act out their ideas on the wall quickly and without the hindrance of managing the rope. To facilitate the generation of concepts, the facilitator provided inspirational artefacts such as elastic bands and several small rounded felt pads which served as placeholder for vibrating motors. By using the felt pads, participants could explore the number, the location and the arrangement on the body of the vibrating motors (see Figure 14, on the left) to inform the form factor of the wearable.

The bodystorming session lasted for 30 minutes; each pair produced one concept and then explained it to the others, who provided feedback on it.

Figure 14. The felt pads used to explore the arrangement of vibrating motors on the body (left); a pair of participants play-testing an idea (right).

Refinement of concepts. For the final part of the workshop, the group moved to the FBK research centre. The change of setting was to help participants detach from the embodied experience and facilitate reflection in a more conducive environment. Participants were asked to sketch an outline of their concept and to refine it according to the feedback they got at the end of the bodystorming session and specifying how to exploit vibration in terms of arrangement of the body, intensity, repetitions, etc., to express the message content they were considering. Because both the climbers and the designers were unlikely to be very familiar with vibrotactile feedback, the facilitator created 18 inspiration cards to support the refinement activity. The cards were inspired by other existing design cards, such as the Design with Intent Cards (Lockton, Harrison, & Stanton, 2010) and the IDEO Method Cards[5]. There were four categories of cards: i) *content of the message*, i.e. what to communicate; ii) *expressive possibilities of vibration*, i.e. how to communicate the message; iii) *interaction*, i.e. how to send a vibration; iv) *form factor and placement on the body.* (For an example of a card, see Figure 15; for seeing all the cards, see the Appendix). Each card had a title identifying the item represented, a short description, and a picture chosen to evoke or illustrate the concept. For example, each card in the 'content of the message' group included a message that could be exchanged by climbing partners during an ascent (e.g. reassurance), examples of verbal sentences used to express such content (e.g. "take a rest!", "breath!"); and then a list of the para-linguistic and non-verbal features of such communications, which might inspire translation to vibrotactile mode, e.g. calm,

[5] https://www.ideo.com/post/method-cards

persuasive voice; low volume; gentle physical touch. The cards were meant to help participants consider aspects of communication that they had not previously taken into account and to motivate their design choices. This activity lasted for one hour.

Figure 15. On the left: a pair of participants reflecting using cards. On the right: two cards for the category 'content'.

In total, the workshop lasted approximately five hours including a one-hour lunch break and the transit time needed from the climbing gym to the research centre. The researcher collected data by taking pictures and notes during the entire workshop, video-recording the presentations of concepts, and collecting the drawings participants made during the refinement phase. The following section describes the concepts which emerged from this contextual co-design workshop.

4.4.3 Findings

The emergent concepts were analysed on the basis of the drawings made during the refinement activity, the audio recordings of the explanations and the feedback received. The analysis considered the product design of the devices conceptualised, the vibration patterns, the content of the communication, and the interaction modalities. The concepts produced were all on the designated topic, i.e. they dealt with communication between climbing partners and they made use of vibration as the communication modality, although to different extents. The concepts addressed different scenarios in climbing, in some cases going beyond the indoor experience in the first phase of the workshop and grounding in personal mountaineering experiences. Each concept is presented in detail in Table 7.

Notably, vibration was used to express a wide range of contents, such as the direction of movement (*pedalboard concept*), reassurance (*necklace concept*), and a general recall of attention for both the climber and the belayer (*points of attention and smartband concepts*).

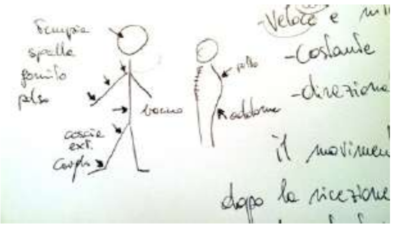
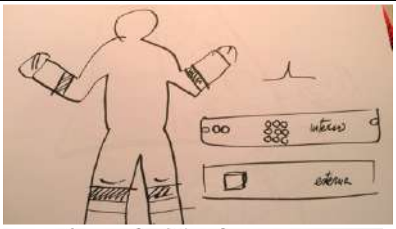
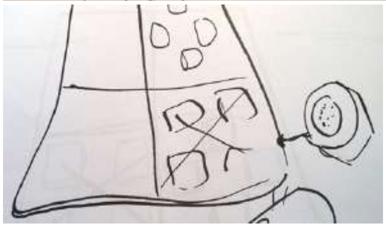
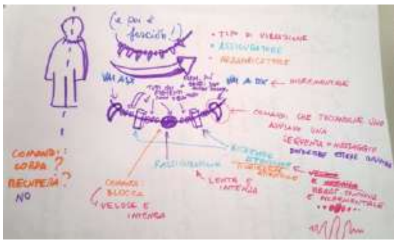
01 - POINTS OF ATTENTION	
	Novice climbers might not know which limb to move first, or be fully aware of their body posture, or they may hold their breath with the tension. This concept proposes that the belayer, who has an external point of view on the climber, sends vibrations to the climber through a speech recognition system in order to recall her/his attention to specific body parts or to the breathing. Several vibration motors are placed along the climber's body, each one corresponding to a crucial joint for climbing movements or on the chest.
02 - DIRECTIONAL MESSAGES FROM A PEDALBOARD	
 	The second concept addresses the problem of how the belayer can suggest to the climber how to move by providing detailed instructions. According to this concept, the belayer has a pedalboard that s/he can use to suggest to the climber which limb to move and in which direction. On her side, the climber wears on each limb a band containing an array of motors that can vibrate in sequence to simulate directions. In addition, the climber can communicate her needs to the belayer by means of a contact microphone inserted into a collar she wears, and the belayer can hear the climber's voice through loudspeakers embedded in the pedalboard.
03 - FUNCTIONAL AND EMOTIONAL MESSAGES THROUGH A NECKLACE	
	This concept proposes that both the belayer and the climber wear necklaces for communicating messages related both to movements and reassurance. Each necklace has five pendants (each with a different shape) that work as buttons and as vibrating actuators. The two outermost pendants are meant to signal the direction of movement; the next ones halfway along are meant to ask for the partner's attention, while the central pendant acquires a different meaning depending on the role of the wearer: for the belayer, it is meant to reassure the climber, while for the climber it is for signalling the need for a rest. Being located centrally with respect to the body, the necklaces can be operated with just one hand, so that the climber does not risk losing her balance and the belayer can keep holding the rope with one hand.
04 - AUTOMATIC STATUS COMMUNICATION THROUGH A SMARTBAND	
	The fourth concept deals with the problem of communication between climbing partners during a multipitch route. It requires both climbing partners to wear a smartband with three LEDs (green, yellow, red) that light up to signal what the climber is doing. The climber's apparel has sensors embedded which classify her movements in three standard situations and code them by colour: moving up (green), setting up a belay station (yellow), being stuck (red). The change of light status is notified by a vibration. The smartband can also be used by the belayer to actively request information from the climber about her status, by sending her a vibration. In this case, the climber would answer by pushing one of the three buttons corresponding to the three coloured LED lights.

Table 7. Concepts from the Contextual Co-Design Workshop.

Different communication purposes influenced the number of vibrating motors and their arrangement on the body, suggesting different shapes of potential wearables. When the vibration is meant to convey indications about movements and posture, the vibrating motors are dispersed along the body resulting in multiple wearable devices worn on the limbs or single motors embedded in clothes, but, while for communicating directions motors are clustered in groups in order to exploit sequential vibration (*directional messages from a pedalboard*), for recalling attention to specific body parts, just one vibrating motor is sufficient (*points of attention*).

Conversely, when the vibrotactile feedback is meant to communicate emotional messages such as reassurance, or to ask about the general state of the person, the vibrating motors are clustered at a single body location (e.g. *the necklace, the smartband*). Vibration is then modulated differently according to the messages to be expressed, by manipulating intensity, repetitions, and the sequential vibration of multiple motors or a modulated vibration 'on the spot' if only one motor is involved.

Three concepts presented a two-way communication (from belayer to the climber and vice versa) and one concept presented one-way communication (from the belayer to the climber, i.e. *point of attention*). All the concepts allowed the belayer to send vibrotactile messages, because s/he has a better view of the climber and the wall and can give suggestions and reassurance without a specific request from the climber. Nevertheless, a remarkable insight from this workshop is that designing wearables for augmented interpersonal communication in the context of climbing raises important issues for input modalities. The feasibility of any technological solution is strongly influenced by the fact that the climber's and belayer's bodies and minds are already engaged in the main activity. In the concepts produced in this workshop, participants made efforts to ensure that the input mode of vibration is conducive to, and not distracting from, the climbing activity. Solutions were variously proposed in the use of voice or feet, in the central location of the wearable on the body, and the touch recognition of different buttons.

4.5 Conclusion

This chapter presents a design process aimed to gather ideas on the possible solutions that wearable devices could offer to climbers' needs. Overall, from this research phase it emerged that, in order to address the difficulties of beginner climbers, wearable devices should increase their awareness of the physical and emotional invisible mechanisms that this sport entail, and a way to do it while respecting the values of the climbing community is to facilitate the communication between the actors involved in the climbing activity. In particular, the concepts proposed have focused on wearables that help the actors standing on the ground to support the climber on the wall. Considering the need for a real time communication in such situation, subtle modalities of communication have been preferred in order not to overload cognitively the climber. To this end, haptic feedback has been deemed the most appropriate to address the situation and exploit the characteristics of wearable devices to be in direct contact with the wearer's skin. Among the different kinds of haptic feedback, vibration has been chosen for its easiness of modulation and low energy consumption. A second workshop was then organised to investigate the use of vibration to augment the communication in climbing. From this workshop it emerged that the expression of different meanings requires different configurations on vibrating motors on the body, suggesting different shapes of potential wearables.

The next section describes the elaboration of the final design and the making of a wearable vibrotactile device that embeds the results of the two previous research phases, i.e. fieldwork and the design process.

05 Prototyping & Evaluation

5. Prototyping and Evaluation

In this section, the design choices, the features embedded by the prototype, and its creation process are reported.

5.1 Design Choices

From the fieldwork, it emerged that technology should help to manage negative emotions, which are closely intertwined to the performance of difficult movements, without seeking to replace the skills of a climber or interrupting the flow of the activity. From the design process, it emerged that wearable technology should help beginner climbers to increase their awareness of emotional states and invisible physical mechanisms by giving feedback in real time and augmenting the communication between the actors.

These insights led to the development of a vibrotactile wearable prototype for augmented interpersonal communication that allows one-way communication from the instructor to the climber. The prototype is meant to allow the instructor to send messages to the climbers to support them when they are in difficulty during an ascent. The communication from the instructor was preferred to the communication from the belayer because often in the learning phase the belayer is as much a novice as the climber and s/he might not have sufficient expertise to give suggestions to the climber. By augmenting the communication naturally occurring in a climbing lesson, i.e. by letting the instructor decide when to send a 'message', the goal was also to make the climber feel reassured by sensing the instructor's attention on her/him and receiving practical suggestions to help her/him to get out of a deadlock.

The wearable prototype consisted of eight devices (Figure 17d, e) composed of four vibrating motors and connected via Bluetooth to a tablet from which they could be controlled individually. The eight devices were designed to cover the eight parts of the body involved in the climbing movements, i.e. the four limbs and the hips with the four directions it can take (front, back, left, and right). Because body and mind are so interdependent in this sport, the choice to deploy the vibration to address difficulties in the climbing movements was also motivated by an interest in verifying whether vibrations for the body would reassure the climber as well.

5.2 Hardware Manufacturing and Product Crafting

Each device consisted of four vibrotactile motors and a board with a Simblee™ RFD77101 Bluetooth Antenna[6] and a small battery of 110 mAh. This system architecture allowed every device to be independent of the others and to avoid long cables that could hamper the climber's movements. It required an ad-hoc board that was designed and manufactured by the electronic engineer of the E3DA research unit in collaboration with two computer scientists of the i3 research unit (Figure 16). In this phase, the researcher/designer actively took part in the discussion, highlighting the objectives and the constraints of the system.

Figure 16. Collaborators discussing about the design of the board.

Initially, the product design of the prototype was driven by the need to protect the components, so it was decided to 3D-print a protective case for them (Figure 17a). Subsequently, because that case did not allow the vibrating motors to get contact with the skin, the design moved to a soft case (Figure 17b, c). The final case was a rectangular fabric envelope with a slot cut in the middle to insert the board and the vibrating motors. The flexible envelope could then be bent and placed over a band so that the motors could stay in contact with the climber's body, whereas the board would stay on the other side of the band (Figure 17e). The first prototype was designed and produced by one of the engineers involved in the making, the last one was crafted by the designer. To place the devices on the four limbs, they were fastened to adjustable bands, while to put the other four devices in contact with the hips they were fastened orthogonally on an adjustable belt. These adjustable bands allowed the devices to be in contact with the user's skin regardless of the diameter of the limbs or the torso.

[6] For further information on the features of the Bluetooth component, see https://goo.gl/GhU6fV

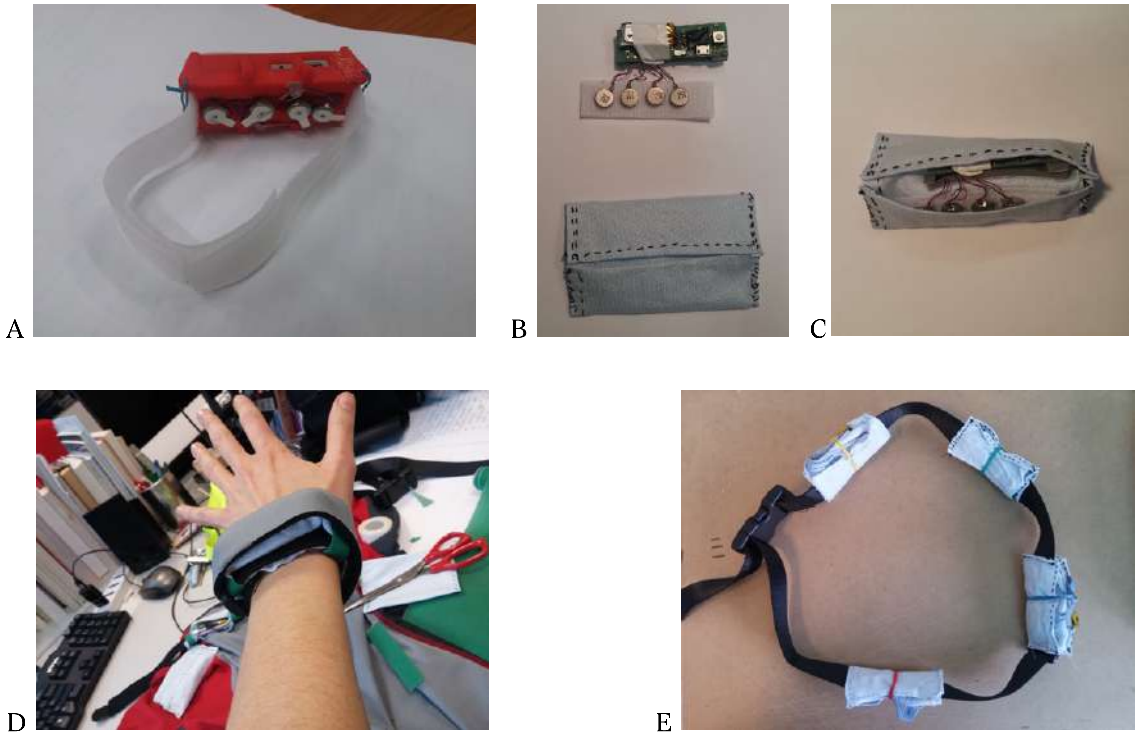


Figure 17. The making of the prototype.

5.3 Software Development and Interface Design

The tablet was intended to be used by the instructor to send a vibration on a specific part of the body to convey messages about movements to do, errors to avoid, postures to adjust, etc. when he would judge it useful. To this end, an android application for tablet was developed which enabled the instructor to send impulses rapidly to one of the eight devices. For this purpose, a Samsung Galaxy Tab S2 8.0 with Android Marshmallow as operative system was used. The app was developed by a collaborator of the i3 research unit, whereas the interface of the app was designed by the researcher/designer. Although the touch-screen interface would briefly divert the instructor's attention from the climber on the wall and the belayer, at this stage the research focus was on the climber's reception of the feedback. A tablet interface was chosen because it is a common, handy device and simple to connect via Bluetooth. The interface on the tablet showed a human silhouette viewed from the rear, mirroring the position of the climber on the wall and reducing the chance of the instructor confusing the right side and left side. The silhouette had a label/button for each point where the instructor could send a vibration (Figure 18). By touching the label, the instructor would send a vibration to that body part. The four motors vibrated sequentially.

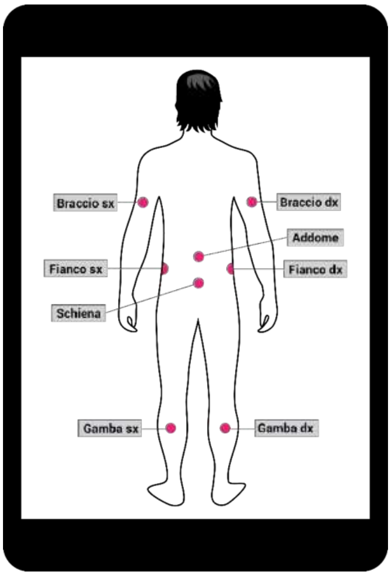


Figure 18. The interface.

The next section will present the evaluation of the wearable vibrotactile prototype.

5.4 Prototype Evaluation

Because the concept of a vibrotactile device still needed to be validated in action, i.e. with potential users in real-life contexts, it was decided to frame the evaluation of the prototype as a 'technology probe' assessment (Hutchinson et al., 2003). A technology probe is a device which usually has a single, very open function, that allows exploring real-world usages in order to inform new designs. In particular, technology probes have the ability to

> *"combine the social science goal of collecting information about the use and the users of the technology in a real-world setting, the engineering goal of field-testing the technology, and the design goal of inspiring users and designers to think of new kinds of technology to support their needs and desires"* (Hutchinson et al., 2003).

This last activity of the research process aimed to assess the utility of the proposed wearable and to answer more specific design questions. Specifically, in this evaluation the probe aimed to investigate:

i) the best location(s) on the body for the vibrotactile wearable devices, in terms of acceptability, comfort, and perceptibility. According to the results of the focus groups, climbers would prefer technology embedded in the gear and apparel they already use, so as not to increase the amount of gear to carry; this study aimed to verify whether fulfilling this need was consistent with the requirements of comfort and perceptibility of the vibration;

ii) the level of perceived usefulness of the wearable;

iii) how climbers would experience the vibration in terms of pleasantness or annoyance.

To answer these questions, participants were asked to try two different configurations of wearables on the body during a climbing lesson in a gym. Because this stage of the research involved the introduction of a new element to an already quite risky activity, the researcher obtained the requisite approval from the Ethics Committee of the University of Trento.

5.4.1 Participants

The participants included a mountain guide (male, 51 years old, two years of professional experience) and 10 of his trainees (five males, five females, age M= 31 years). When the researcher contacted the guide, he was about to finish teaching two courses and start a new one; therefore, the trainees' level of climbing experience varied: four were absolute beginners about to start their first course, four had just finished a beginner course, and two had just finished an advanced course.

5.4.2 Procedure

The investigation sought to compare the efficacy and pleasantness of identical information conveyed to different points of the body. Two different configurations of the eight devices (SET1 and SET2, see Figure 19b) were chosen, based on the most important parts of the body usually employed in climbing: the hips, the oscillation of which allows climbers to shift their weight and manage their balance; the legs, for pushing the body up; and the hands as support for keeping balance and pulling the body up. The configurations were as follows:

1. In SET1, the devices for conveying communications about the hands and the legs were placed on wrists and ankles respectively, while devices for communications relating to the hips were arranged on a belt placed below the chest.
2. In SET2, the devices for conveying communications about the hands and the legs were placed on the deltoid area and inside the harness thigh bands respectively, while the devices for communications about the hips were arranged on a belt placed just above the harness.

The preference for one configuration or the other would influence the design of the final system. For example, if the vibration was perceived better on the wrists and ankles, it would suggest the design of a kit of auxiliary artefacts, such as belts/bracelets; conversely, if the vibration was perceived better on the shoulders and thighs, it would be better to embed the vibration actuators in the climbing gear and apparel (for example, in the T-shirt for the shoulders, in the thigh bands for the legs, and in the harness belt for the hips).

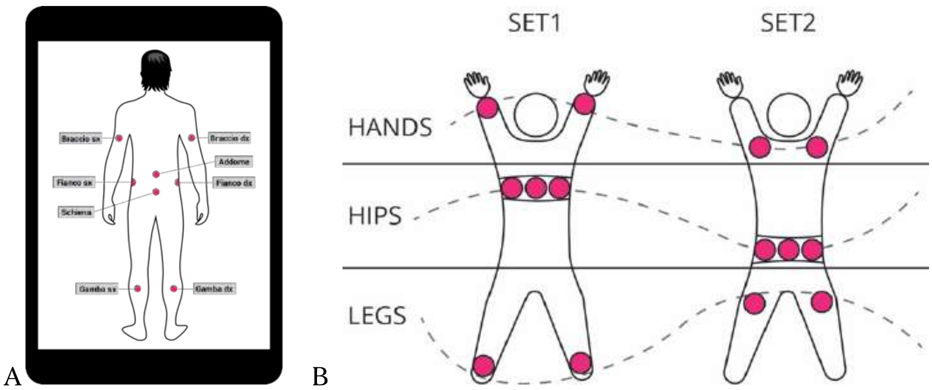


Figure 19. A) The tablet interface S; B) SET1 & SET2.

The study was organised in three sessions in order for the facilitator to have smaller groups of participants and make it easier to follow the activity closely. Each session lasted on average two and a half hours. At the beginning of each session, the facilitator explained to the participants that the system allowed the instructor to send a vibration to one of the body parts where the climber was wearing the devices, without giving any detailed explanation about the possible meaning of the vibration. This left a lot of flexibility in the use of vibrations and free interpretation of the purpose of the system. The instructor was asked to send the vibration whenever he thought it necessary. In this way, it was possible to assess the perceived usefulness of the wearable, even if to the possible detriment of the assessment of feedback perception on all parts of the body bearing the devices. Leaving the decision-making in the instructor’s hands reflected the researcher's aim to create study conditions which resembled usual practice 'in the wild' as far as possible. At the beginning of the first session, the instructor was made familiar with the vibrations and the tablet interface, by wearing a bracelet and feeling the intensity and duration of the vibrations on his own wrist.

To reduce the risks associated with introducing cutaneous feedback to climbers which they were not accustomed to, each climber was asked to climb in top-rope on a route which was challenging for them but not too difficult (based on their own or the instructor’s judgement). Before beginning the route, they were also made to familiarise with the sensation of the vibration on all relevant parts of the body. The number of available devices was enough to 'dress' one climber at a time, therefore the session was organised as an assembly line, with each climber trying a configuration at a time and one after the other. Five climbers tested the configuration SET1 first and SET2 second, while the other five climbers took the reverse order, to counterbalance the effects. Climbers were asked to fill in a questionnaire after trying each configuration, and a comparative questionnaire after trying both (Figure 20).

Figure 20.

The questionnaire completed after each configuration trial investigated the level of comfort of the wearables, the discomfort generated by wearing them, and the perceptibility and usefulness of the vibration. The intensity of sensations was measured via Likert scales ranging from 1 (low) to 5 (a lot), while the effects of the vibration on the mood and the cognitive load of the climber were investigated using semantic differential pairs (distracted/focused; unsafe/safe; relaxed/stressed), as were the perceived qualities of the vibration (expected/unexpected; weak/strong; irritating/delicate; hurting/itching). In the comparative questionnaire, climbers were asked to express their preference about the devices' locations on the body, by comparing the two configurations for the upper limbs (wrists versus shoulders), for the hips (low versus high belt), and for the lower limbs (ankles versus thighs). First, they had to express their preference in absolute terms and to explain it in their own words; then they had to mark their preferences in response to closed questions along five dimensions, namely i) comfort, ii) intuitiveness (i.e. appropriateness of that body part for the communication conveyed), iii) ease of perception, iv) acceptability, and v) perceived usefulness. Additionally, the researcher took notes and pictures during each session of the study and conducted an interview with the instructor at the end of each session.

5.4.3 Findings

In this section, results from both the qualitative and quantitative analysis are reported together and structured according to the main themes investigated or emerged. Quantitative data are summarised as index values (mean of scores for each questionnaire items). No statistical differences emerged by the comparison between the two configurations.

Sense-making of the vibration. As explained above, no specific instructions about the use or meaning of the vibration were provided to the participants. Therefore, at the beginning of every ascent, the guide and the climbers needed to negotiate the meaning of the vibrations (P09: "*So, I feel the vibration and then what do I do? Do I have to turn and speak to you?*"). This level of openness in the design allowed the participants to adapt the wearable to the different learning needs of each trainee. The guide experimented with two main uses of the vibration:

- Signalling errors: "*I send you the vibration when you do something wrong, so when you feel it, you stop for a while and think of what you could have done wrong*" (Guide).
- Suggesting the right movements to do, especially focusing on the hips, e.g. either to suggest shifting the weight of the body onto one leg before starting to move up: "*If I send you a vibration on the right side, it is because you need to load your body weight on the right leg and move the left foot*" (Guide); or to suggest bringing the hips closer to or further from the wall.

The guide observed that he typically used the vibration to signal errors either to the more experienced trainees or to the complete beginners who were still unknown to him. Conversely, he used the suggestion mode with the beginners he was already familiar with and who still needed to assimilate the proper movements but who already had a sense of how to perform them

> *"To the trainees of the beginner course, I wanted to give a suggestion about what limb to move first, so I was sending the signal before the movement; while to the trainees of the advanced course, I was signalling an error in a movement already performed"; "This time I haven't sent the signals to the hips so often, mainly because I haven't spoken yet of these things with the guys... It's the first time I meet them, so if I told them to shift the hips sideways, they would not even know what it means"* (Guide).

A participant pointed out that the meaning of a vibration might depend on the climber's status, i.e. if the climber is moving, the vibration could signal an error; while if the climber is stuck, it could signify a suggestion about what/how to move.

Expressive capacity of the vibration. Soon the guide realised that the vibration could be used to refer only to the climber's body and movements, and not to the climbing wall ("*Sending feedback on the hips works, the problem is when a climber uses the right foot on the wrong* *foothold.* [How can I signal that?]"). In order to increase the expressive capacity of the vibration, P10 suggested increasing the number of devices or differentiating the kinds of vibration within the same device ("*Maybe it could be useful to have two actuators on each leg, one on the right side and one on the left side, or two different kinds of vibration in order to know in which direction the leg should be moved*" - P10).

Reception and interpretation of the vibration. Some interesting issues were raised in terms of interpersonal communication mediated by the tool. On the one hand, the instructor was not always sure whether the vibration was perceived by the climbers, and on the other hand, when climbers perceived it, they were not sure how to interpret it. A few times the guide sent the vibration, but the climber did not show any reaction ("*I'm sending her the vibration, but she doesn't feel it*" - Guide), leaving the doubt whether the system did not work, or it worked but the climber was too focused on the route to perceive it or s/he perceived it but ignored it. For this reason, one climber chose to address the instructor's need for confirmation by answering "*Received!*" to every vibration she perceived. Another issue was that once the climbers received the vibration, it was not always easy for them to understand the error it was meant to signal. Usually, if the climbers were still low enough on the wall, they would speak about it with the guide (Figure 21), for example:

Guide: "Did you receive my vibration?"

P01: "Yes, but I did not understand want you meant"

Guide: "You lost your balance because…".

Otherwise, if it was not possible to hear each other, the climbers would continue to climb following the suggestions when possible. Then, after each ascent, the guide had a chat with the climber, summarising all the vibrations he sent and what he meant by them.

Figure 21.

A notable exception is what happened with P07. When P07 received the first vibration, he was still close enough to the ground to be able to speak with the guide, but when he asked for explanations the guide told him "*try to think of another solution*", basically adding no further information to the vibration and leaving it to the climber to identify the error and the solution. It is likely that the guide's decision was due to this participant already having some knowledge of climbing. P07 later affirmed this in the questionnaire: "*the guide's voice helps since it mentions clearly the mistake, but it is not fundamental since the most important thing is to identify the body part*." Another participant suggested exploiting the open nature of the system to adapt to the individual needs of each climber, "*it would be useful to reveal in advance the most typical errors of a person so that it would be possible to associate the vibration with the kind of mistake and correct it immediately*" (P08). These findings show that the ambiguity of the vibrotactile wearable communication could be helpful to foster active learning by trainees and personalisation of the system.

Preferences about location on the body. In general, participants found wearables in SET1 and SET2 equally comfortable, with 3.7 points on average. They were not embarrassed to wear the devices on any part of the body proposed (all participants put 1 in the Likert scale in both conditions). However, when comparing the corresponding body locations, different patterns of preference emerged. Between wrists and shoulders, six out of eight people preferred wrists (two people did not express their preference because they received no feedback for the upper limbs) along all the five dimensions. In their comments, participants remarked that wearables on the wrists were more comfortable and more intuitive, less invasive and less distracting. Further, wrist devices did not interfere with the rope, and allowed a clearer perception of the vibration. When choosing between a belt on the chest (high) or on the abdomen (low), six out of 10 participants preferred the abdomen for the same reasons they preferred the wrists. However, looking more closely at the comparison, the difference between the two positions was not very marked; participants rated the level of comfort of the high and the low belts as equal (four mentions each and two for 'both'), while the perceptibility of vibration in the higher belt was clearer (five mentions for the higher belt, versus three for the lower one). Both belt positions were judged useful and appropriate to the same extent, for the kinds of communication they conveyed (six mentions each). Between thigh loops and ankle bands, the latter were strongly preferred (nine out of 10) on all the five dimensions. Participants found them more comfortable (six), the perception of the vibration was clearer (two), and the information was more intuitive (three). The guide expressed his opinions about the best location on the body in terms of usefulness: "*in* *climbing, everything starts from the hips and climbers make errors with their feet, I sent almost no feedback on the hands*".

Perceptibility. Participants perceived the vibrations more clearly on the hips in SET2 (five entries) and on the ankles in SET1 (five entries). However, in no case was the vibration clear enough to allow participants to determine the correct number of vibrating motors and the kind of vibration. There were four vibrating motors and they vibrated sequentially in both sets. Climbers perceived three motors on average and these were perceived mainly as vibrating simultaneously (eight entries in SET1, five in SET2). It is possible that the perception of the vibrating motors was influenced by:

- The sensitivity of the parts of the body where the devices were placed and the level of adhesion to the skin.

- The level of the climbers' cognitive engagement with the route due in part to its difficulty, e.g. "*I was distressed, and I wasn't able to perceive the vibration anymore*" (P08), "*This time I was tired, and I was climbing on a hard route for me, so I focused less on the vibrations and much more on the holds. Moreover, the belt on the chest tended to slide down*" (P07).

- The distance between each vibrating motor, which could have been too small for climbers to determine the number of motors correctly.

Finally, the intensity of vibration was perceived as slightly stronger in SET2 (3.3 on the Likert scale, versus 3.1 of SET1), but also slightly more annoying (2.5 of irritation against 2 in SET1).

Effects on the climber's cognitive status. The level of surprise with which climbers received the vibration was high in both conditions (3.6 in SET1 and 3.8 in SET2). This might have related to the climbers' level of self-awareness or the level of cognitive engagement. In both conditions, the vibration was considered to support the focus of attention on the ascent (the score was on average 3.1) but, at the same time, it also stressed the participants slightly (with an average of 3.1 in SET1 and 3.3 in SET2) probably because it signalled that something they were doing required adjustment. Nevertheless, knowing that they could receive a vibration at some point seemed to improve their sense of safety (with 3.3 in SET1 and 3.5 in SET2), e.g. "*I felt indirectly safer because I was sure that who is standing on the ground is looking at me and not around*" (P09).

Perceived Usefulness. Participants found the system very useful (4 points on the Likert scale) and affirmed that they would accept it in a climbing course if the instructor proposed it. They affirmed that it was

> *"a very interesting system, useful to improve the body posture"* (P05);
>
> *"the vibration is very useful to stop and be able to immediately correct the mistake"* (P08);
>
> *"I believe that this system is absolutely useful; maybe it is more suitable for beginners, but it can be used for improving at every level"* (P07).

Specifically, participants said that the system helped them understand their errors, recall their attention to their technique ("*to focus more on the right technique*" - P09), and they valued the instructions ("*they enhance the voice indications*" - P03, "*Used in this way it is much more useful, I usually never unload the foot the I want to move next*" - P01). This usefulness was perceived as especially high because the feedback was in real time ("*to understand immediately what I was doing wrong*" - P08). Some participants reported that the system would be more helpful with the integration of voice indications from the guide, "*also the vibration per se is useful, but accompanied with the voice indications it is much better*" (P08); while others commented that to really appreciate the system, climbers need to get used to it: *"it needs to be used with continuity; the first time you wear it you don't really appreciate it, it's a new tool, it requires familiarisation*" (P08).

The guide found the system quite useful too:

> *"At the beginning, I thought it would have been more useful for beginners, instead now I think it's a useful system for those that know already the basics of climbing" and "I think this system would be especially useful for disabled people such as deaf and blind people, and for children as a playful experience".*

In his usual teaching methods, the guide used a laser pointer to indicate the holds to his trainees, so the researcher asked him to compare the laser pointer to the vibration system and he affirmed that

> *"the laser pointer has a good reach, but on the other hand, when using it, very often climbers get distracted because they focus more on searching for the light than on what they are doing. Maybe with this [vibration] system,*

climbers can keep being focused and notice the errors only when I signal them".

Timing. The perceived usefulness was closely related to the timing of the vibration. Although four out of six participants affirmed that the guide's timing of the stimulus was generally good both in SET1 and SET2, sometimes they were not satisfied with the timing. As P01 described, there are three kinds of timing problems:

- the vibration does not arrive because the guide wants the climber to find the solution on her/his own ("*I think it's difficult to understand which is the right moment to send the vibration: the instructor usually waits before sending the signal in order to see whether the trainee understands what to do by herself, but it may happen that in the meanwhile it is the trainee who asks for help because she doesn't know how to solve her problem*");
- the vibration arrives too late, i.e. when the trainee is already correcting herself and the feedback generates confusion ("*sometimes the vibration arrived when I was already doing the* [correct] *movement that the instructor wanted me to do*");
- the vibration is premature, and the trainee would prefer to reflect on the movement before intervention ("*sometimes the vibration arrived too early and I would have preferred to have some more time to think of a solution by myself*").

For the guide, it was difficult to send the vibration at the right moment because of the continuity of the climber's movement ("*he climbs fast, it's hard to send him feedback*") and the visual interface for sending the vibrations

> *"it would be better to have something that you don't need to look at to give instructions, like for example a joystick, because, by the time I look at the interface, the climber has already moved forward and is performing the next movement"* (Guide).

One trainee suggested pairing the vibration with the guide's voice instructions to improve the timing of the feedback, "[I think the system would work better] *in this way: while the instructor is speaking, when he mentions the right hand, he sends the signal to that part of the body too*" (P02). The possibility to catch the right timing remains one of the key aspects of this system ("*The best aspect of the system is the immediacy of feedback*" - P08) and a challenge worth exploring.

Although no statistical difference occurred, climbers expressed a slightly higher preference to wear the vibration devices on the wrists, ankles and abdomen, having considered alternative configurations on the body. These positions were found to be more comfortable, more sensitive to vibration, more appropriate for the message content and more socially acceptable. Moreover, participants found the communication system useful overall; climbers valued it because it made them aware of their mistakes working as a reminder or nudge, while the guide valued the fact that the system works in real time but does not distract climbers from the ascent. The vibration was not always easy to interpret, but its ambiguity of meaning had the advantage of fostering active learning and personalisation of the training. Since vibration can refer only to the parts of the body where it is applied (and not to the context), it was demonstrated to be particularly suitable for enhancing proprioception. It was used either to signal errors (i.e. as feedback) or to give instructions (i.e. as feedforward). In both cases, appropriate timing of the vibrations was important for interpretation of signals according to their agreed meanings and for the system to maintain its usefulness. Although the vibrations surprised and stressed climbers a little, it also helped them to focus more on the climbing technique and to feel safer. The probe identified two areas of potential improvement: implementation of bi-directional communication to make the instructor aware that the climber has received the vibration; and development of an input interface for instructors which does not catch their attention too long and allows them to intervene quickly in case of need, e.g. holding the rope.

Overall, a key strength of this vibrotactile wearable appears to be its adaptability to individual learning needs and to the progressive evolution of a climbing course. These findings, along with climbers' preference to wear the devices at the ends of their limbs, complement the findings of the focus groups where it emerged that because climbers need to minimise the amount of gear they carry, they would not accept additional artefacts unless the new items were regarded as extremely useful. These results suggest an opportunity for a kit of lightweight hybrid vibrotactile wearable devices such as strings or patches that can be adapted to the individual body shapes. This kit should be given to the instructors who can deploy it according to their teaching goals at the time and integrate it with other teaching tools.

5.5 Conclusion

This chapter presented the development, implementation and evaluation of a prototype based on the requirements emerged from the previous two research phases. This prototype is a tool for augmenting communication in the context of learning to climb. It consists of eight vibrotactile devices to be worn by the beginner climber and a tablet that allows the instructor to send vibrations to one of the eight devices at a time. The evaluation of this wearable system has been conducted ‘in the wild’, i.e. in a climbing gym, and the prototype has been considered as a technology probe, i.e. the purpose of the prototype was intentionally left open so that participants could find their own use and meaning of it within the sport practice. From the evaluation, it emerged that the instructor appreciated the possibility to send a vibration in real time and to confer different meanings to it (e.g. feedback or feedforward). Moreover, he appreciated the fact that vibration, for its own nature, is a feedback that directs the attention towards the self and not towards something external, thus fostering focus. The system was appreciated also by the trainees, who found it useful to focus and helpful to improve their performance and, even if at times they were caught by surprise by the vibration, they felt reassured by knowing that the instructor was paying attention to them. These results, together with trainees’ preference to wear the devices at the ends of their limbs, indicate the possible usefulness of a kit of wearable devices to be given to the instructor as auxiliary artefact to support the teaching of climbing and the possible acceptance of a wearable device that augment the communication in climbing.

06 Discussion & Contribution

6. Discussion and Contribution

This chapter discusses how the research work presented in this thesis has addressed the initial research questions and illustrates its contributions to the field of HCI and sports.

6.1 Discussion

The research work presented in this manuscript was motivated by the interest to investigate *what are the elements to consider in order to design wearable devices for sports that are useful, acceptable, and desirable*. Grounding on the widespread dropout of wearable devices reported in several market and research studies (Canhoto & Arp, 2017; Ledger & McCaffrey, 2014; Shih et al., 2015), this research was based on the assumption that sport practice cannot be reduced to the only performance and that presumably current wearable devices do not address the full range of needs of sportspeople. Starting from these premises, the research process presented here has adopted a Practice Perspective (Kuutti & Bannon, 2014) and a methodology based on the embodiment, situatedness, and the involvement of the potential users in order to gain a more empathic understanding of the case study analysed (Wright & McCarthy, 2008). To contextualise the research in an actual setting, climbing was chosen as the case study and the main research question was broken into two operational sub-questions. The two sub-questions were: i) *what elements constitute the practice of climbing*? And ii) *how can wearable devices support such practice*?

The first research sub-question (i.e. *what elements constitute the practice of climbing*?) was addressed in the fieldwork, during the Understanding Phase of the research process. The investigation was conducted through methods that favoured the researcher's presence in-situ, such as field observations, and the involvement of potential users, such as interviews with beginners and instructors, and focus group with experienced climbers. The elements constituting the practice of climbing identified are a performance based on precise and efficient movements, the climber's emotions and trust in the partner, and the values of the community of climbers. The climbing performance requires a kind of engagement for the climber which is not only physical but also cognitive and emotional. When learning this sport, such performance entails specific learning needs and corresponding teaching strategies. The emotions present in climbing are both positive and negative. The positive ones consist in the feeling of a high level of self-efficacy that originates from the successful accomplishment of a route, and the feeling of agency on the environment that originates from being in contact with nature. Typically, these positive emotions are experienced by expert climbers, while for beginners they are a status to achieve. On the contrary, negative emotions, such as discomfort and fear, are more frequent for beginners and occur during the performance. They are due to having to move along a vertical wall, a type of movement that is not familiar to many people and requires the acquisition of specific movement patterns and skills to maintain the balance and avoid falling. The values of the climbers' community resonate with the positive emotions of the sport and consist of gaining the necessary expertise to tackle a climbing route, establishing a trade-off between safety and adventure, and belonging to a sub-community of climbers. These values create a vision of the sport that shapes the motivations and the goals that climbers have to practice it and is reflected in the settings and the artefacts chosen for the practice. For example, climbers with a higher expertise and keener on adventure than on safety might choose to practise trad climbing in the Alps, whereas beginners might prefer climbing indoors. Overall, the fieldwork has produced an in-depth study, where several practices, experiences, and points of views on the sport were collected, considering all the different roles and level of expertise involved in climbing. The elements constituting the practice of climbing are reported in the Findings of the Understanding phase (sections 3.2.3, 3.3.3, 3.4.3) and have been operationalised for the design in Opportunities and Constraints in the sections 3.5.1, 3.5.2. It is worth noticing that the Fieldwork studies have been conducted indoors. This was done because climbing has the peculiarity that can be practised both indoors and outdoors and climbing gyms where chosen as setting for a matter of practicality. The conduction of studies outdoors could have provided a slightly different view on the practice, e.g. it might have shifted the focus more towards the environment, and consequent different insights. Still, the outdoor dimension has always been actively investigated and considered in the design process. It emerged in the aspirations of beginners, in the ultimate goals of mountain guides, and in the stories of expert climbers.

The second research sub-question (i.e. *How can wearable device support the climbing practice?*) was investigated in the design process presented in Chapter 4 and in the evaluation of the prototype presented in Chapter 5. The challenge of understanding how a wearable device could address the design opportunities identified in the fieldwork while also respecting the constraints has been addressed through two co-design workshops and a technology exploration. The first workshop has gathered together designers with a personal expertise in climbing and other outdoor sports to explore the design space emerged from the fieldwork. From this workshop, it emerged that wearable devices could support the practice of climbing by augmenting the communication between the actors involved, so that technology would pose itself as a facilitator of the exchange of climbers' expertise, rather than a substitute, and thus addressing also the need for mutual trust and reassurance.

Moreover, during the workshop it was noted that introducing a communication technology in an activity with high cognitive involvement such as climbing, would have required a subtle communication. In this regard, the best communication modality to be subtle and exploit the quality of wearables to be in contact with the skin has been identified in haptic feedback. The subsequent technology exploration identified vibration as the most appropriate haptic feedback modalities for the case study considered for its easiness of modulation and low battery consumption. In the second workshop, climbers and designers' competencies have been intertwined in order to gain an empathic design. This workshop showed that the meanings of the vibrational messages might depend not only by the modulation of vibration, but also on the body part where the vibration is applied. Despite the different level of embodiment, situatedness, and involvement of participants that has characterised the workshops, both have provided useful insights about how to proceed on the design of the device.

The findings emerged from the fieldwork and the insights gained from the workshop have been considered in the implementation of a prototype, which resulted in a wearable system aimed to enable instructors to send vibrations to beginner climbers while they are on the wall in order to recall their attention. From the prototype evaluation in the wild, the system received a positive assessment both from the instructor, who appreciated the possibility to send a 'nudge' in real time adapting it to the learning needs of each trainee, and from the trainees, who valued its ability to remind them of the proper performance while feeling reassured by the awareness that someone on the ground was paying attention to them. A limit of the prototype is that it lacks a system of confirmation to inform the instructor that the vibration has been received. Moreover, the prototype is very useful to give feedback about posture and proprioception, but it needs to be accompanied by voice instructions if the instructor wants to refer to the wall. From a methodological point of view, the process of meaning making and appropriation during the evaluation has been well received since it has led to the personalisation of the vibration with each one of the climbers and to avoid passive learning in the trainees. Conversely, a possible limitation of this last study could be that the prototype resulted from an indoor investigation and was evaluated indoors as well. In order to prove its usefulness and acceptability in climbing in general it would benefit from an evaluation also in outdoor conditions. Moreover, during this evaluation the focus of attention has been more on the function of the prototype, the perception of the vibration, and how to implement the interaction in order to make it acceptable, rather than on the look and feel of the prototype or the input modality for the instructor. However, this evaluation should be considered as the testing of the minimum viable product for considering the production of a commercial system or the implementation of a functionality for augmented interpersonal communication in an already existing wearables for sports.

The work presented in this manuscript answers the main research question "*What are the elements to consider for the design of useful, acceptable and desirable wearable devices for sport*?" limitedly to outdoor adventure sports. It does so by offering a conceptual framework that articulates the aspects composing the practice of outdoor adventure sports with the aspects underlying the design of wearable devices and orchestrating them through a methodology that guarantees the usefulness, acceptability, and desirability of the devices by the users.

The common definition of outdoor sports is quite unclear. Often the meaning is taken for granted and is very wide, considering all the sports that are carried out outdoors, and thus including also sports such as cycling and running. This thesis adopts a definition of outdoor adventure sports inspired by the definition of 'outdoor adventure' given by Pike & Beames (2013) and Müller and Pell (2016), and that of 'life style sports' given by Weathon (2004). The definition of outdoor adventure sports adopted here includes *the sports that require the challenge with oneself through the exploration of nature and the tackling of a natural element, such as the verticality of mountain walls, the deepness of water in scuba-diving, the snow in backcountry skiing, the rough surface of a river with a kayak. These sports are characterised by an individual performance but are conducted in group in order to minimise risk*. Therefore, the performance of this type of sports require physical preparation, knowledge of the environment and of the gear to tackle it, psychological and emotional firmness, and coordination with the sport partners.

The framework developed in this thesis is limited to outdoor adventure sports because it is based on the findings emerged from the investigation of climbing, an outdoor sport that consists of tackling it vertical rock wall and moving along it to reach the top, by managing a rope and coordinating with a partner. Although climbing has been the only case study analysed and the studies have been conducted indoors, the investigation has always considered the outdoor dimension of the sport. The generalisation to other outdoor adventure sports is based on the comparison of the results of the case study analysed with the literature of psychology, sociology and HCI for sports.

The framework identifies the elements that compose the practice of outdoor adventure sports and explains how these elements influence each other and the elements of product design and technology that compose a wearable device. The usefulness, acceptability and the desirability of the device are guaranteed by a research methodology that is based on embodiment, situatedness, and user participation. In particular, the usefulness is provided by grounding the creation of a new technological artefact in the already existing practices of the outdoor adventure sports, which means starting the investigation from the study of the practices and from there drawing the needs of sportspeople that inform the shape, implementation modalities and the role of technology. The acceptability is provided by the consideration of the outdoor values in the design and by making it a shared process with the potential users. Finally, the desirability is provided by answering a real need and maintaining the system sufficiently open to ensure meaning making by the users and thus paving the way for appropriation.

In the next section, the contributions that this thesis brings to the domain of HCI and sports at different levels will be clarified: sports in general, framework for outdoor adventure sports, design space and prototype for climbing.

6.2 Contribution

So far, the majority of HCI studies has framed the problem of how wearables could support the domain sports in terms of improvement of the physical performance. A few initial studies advocate for the need of a deeper investigation that widens the field of vision of HCI for sport towards elements of sociality, experience, culture, and emotionality (Cheverst et al., 2018; Havlucu et al., 2017; Tholander & Nylander, 2015). This thesis has tackled this challenge and has attempted to offer a new perspective on the design of wearable devices for sports. Specifically, this thesis contributes to the domain of HCI for sports by offering:

1. A methodological contribution, which applies to sports in general. This methodological contribution consists in framing sports as socially shared and culturally defined practices as well as personal experiences composed of physical, sensorial and emotional involvement. The methodology adopted in this thesis was based on a Practice Paradigm perspective and on the principles of situatedness, embodiment and co-design. This methodology was adapted to the domain of sports, where situatedness and embodiment have been orchestrated with co-design in order to ensure an understanding of the sensorial involvement and tacit knowledge of sport to both the researcher and the participants, thus fostering an empathic design solution. Furthermore, following this methodology the wearable technology produced has been left to acquire meaning by placing it within the practice of the sport.

2. A conceptual framework that articulates the design of wearables for outdoor adventure sports, in order for them to be meaningful to the potential users, and thus pave the way for a better acceptance and long-term adoption. This framework is the result of the comparison between what emerged from the research and design process on climbing and the literature on outdoor sports and on the design of wearable devices. It breaks down the complex character of the outdoor adventure sports practice by identifying the elements that compose it and showing how these elements inform the specific product design requirements of a technology meant to be applied to the body, such as wearables. The elements identified include the sport culture, activity, the physical, cognitive and emotional involvement of the sportsperson as well as the aspects of the wearable device both as a technological and aesthetic artefact. This holistic vision, which includes elements of the sport practice other than performance, has not previously been considered in HCI.
3. A kit of vibrotactile wearable devices for augmenting interpersonal communication in rock climbing, which is the result of the identification of a design space that includes elements of the sport practice other than performance. In particular, this thesis expands the design space of wearables for climbing to the emotions and values involved in the sport practice and opens up to new roles beyond that of activity tracking. In the case study analysed in this thesis, this new role has been identified in supporting the relational aspect of learning by enhancing interpersonal communication between the sport participants.

In the next sub-section, each contribution will be explained in detail.

6.2.1 Integrating Situatedness, Embodiment and Co-design in the Sport Domain

From a methodological point of view, this thesis considers both the collective and cultural dimension of the sport practice and the individual dimension of the sport experience. In order to do that, this thesis has adapted a methodology based on the principles of situatedness, embodiment and participation of potential users to a new domain – that of sports. This methodology was chosen because the human body is pivotal both for the activity investigated, i.e. sport, and for the technology to be designed, i.e. wearable devices. The materiality of both sports and wearable devices and the consequent high level of sensorial involvement that they entail required methods involving presence, first-hand experiences, and body involvement in real-life context. A similar set of methods has already been adopted for the investigation of advanced amateur runners (Knaving et al., 2015) where the authors observed and interviewed runners in context and took part in a half marathon. However, the work presented here differ because it has incorporated the principles of this methodology during the entire research process by adapting the methods to the different phases and actors involved. Indeed, the combination of situated and embodied methods with a co-design approach has required to create the conditions for an understanding of the sensorial involvement and tacit knowledge of climbing also by the designers participating to the co-design workshops. The choice of involving climbers and designers in a bodystorming in the context of a climbing gym had the purpose to develop more empathic and situated design concepts. Finally, the evaluation was organised to make the climbers and instructors try the prototype 'in the wild', i.e. in a real situation in an ecological context, so that they could experience it and confer meaning to it within the practice. Because all sports are characterised by a strong physical, sensorial and situated dimension and in light of the original, pertinent, and salient findings that these methods have provided in this thesis for the production of a technology that is useful, acceptable, and desirable by its potential users, this methodology is suggested for the design investigations of sports in general, not only of outdoor sports.

6.2.2 Conceptual Framework

This thesis presents an original contribution to the design of wearable devices for sport by offering a conceptual framework for the holistic design of wearable devices for outdoor adventure sports. This framework is motivated by the lack of systematic knowledge in HCI on the various elements that compose the sport practice and on how they can influence the design of wearables for sport. The framework is based on the empirical work conducted in this thesis and the comparison and integration of findings with the scientific and design literature on HCI and Sport. The investigation of the design of useful acceptable and desirable wearable devices in climbing, which is an example of outdoor adventure sports, highlighted a number of focal aspects of the sport practice that need to be considered in the design of wearable devices. This framework identifies and articulates the elements that characterise the sport practice of outdoor adventure sports and their orchestration with the technological, product design and cultural aspects of wearing an artefact on the body. The aspects that pertain to sport practice are i) the sport activity, ii) the sportsperson, and iii) the sport culture, while the aspects that compose the wearable are i) the product design and ii) the technology. For a general overview see Figure 22; for a more detailed description see Table 8. Each of these aspects is composed of sub-elements that clarify the articulation of the framework, and each element is explained through examples from the outdoor adventure sports domain. The framework is intended to be a generative tool for supporting HCI researchers, practitioners and designers in the design of wearable devices for outdoor adventure sports.

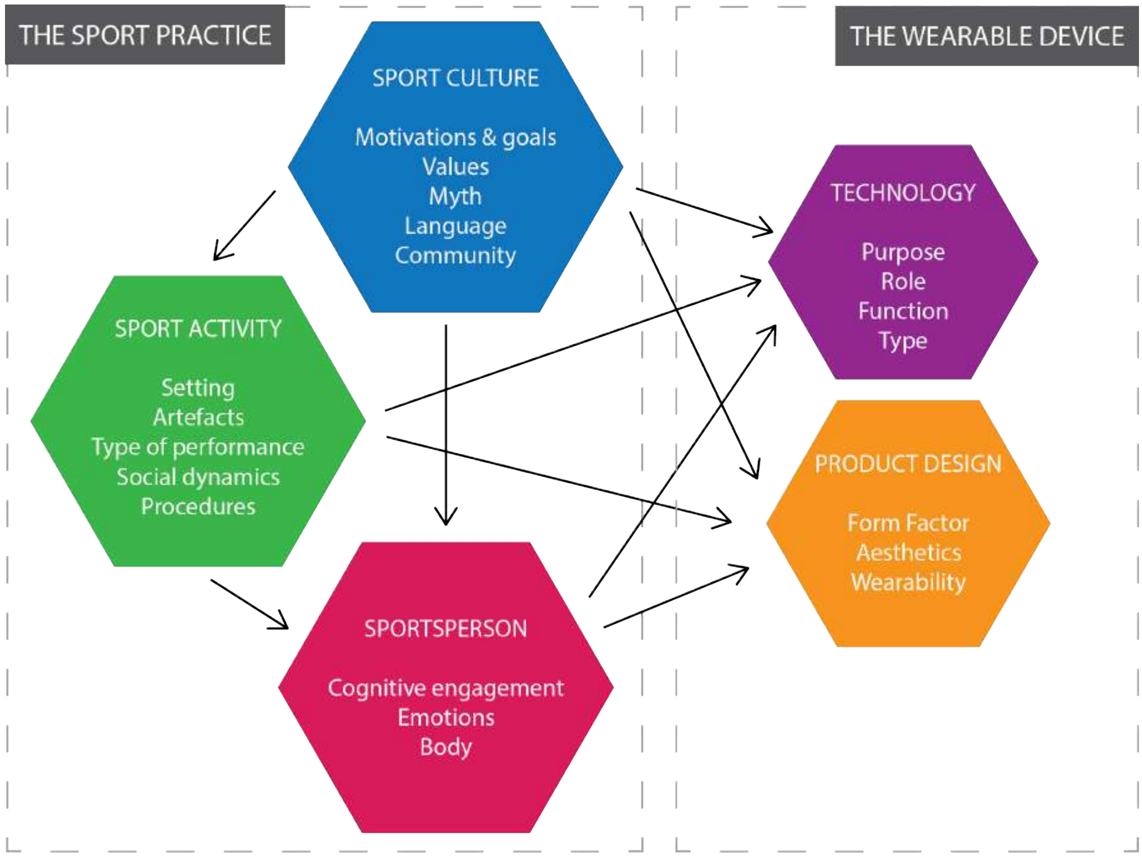


Figure 22. Overview of the conceptual framework and its articulation.

The sport culture. The sport culture is a pivotal aspect in the definition of the sport practice because it explains the motivations to practise a certain sport and the strive towards sport goals. The sport culture consists of a set of values and myths shared among the community of people practising the same sport. Because outdoor adventure sports are characterised by the challenge with the environment (which is rather a challenge with the self through the environment), people who practise them are moved by the values of adventure and exploration (Brymer & Gray, 2009; Müller & Pell, 2016), the cult of self-efficacy and expertise (Byrne & Müller, 2014; Levenhagen, 2010; Cheverst et al., 2018) to do their sporting explorations in safety conditions (Desjardins et al., 2014), and the sense of belonging to the sub-community of sportspeople who share the same vision of the sport (Dutkiewicz, 2014) . The values are reflected by the myths and the narratives of the community, i.e. who to admire among the past and present sportspeople (e.g. the pioneers of alpinism) and which performances to consider excellent (e.g. timing an ascent for a

Yosemite Park route, the braveness of soloing[7] a route, etc.). The values are also realised through the procedures, artefacts, and the relationship with the environment when they practice their sports. For example, from the fieldwork of this thesis it emerged that within climbing there is a significant cultural difference between sport climbing and alpinism, highlighted especially during the focus groups (Section 3.4). Sport climbing typically consists of one-pitch ascents, uses permanent bolts in the rock wall as protection, and the good performance is achieved through fluent and effective movements. Alpinism on the other hand has the primary goal of reaching the mountain summit, it involves multiple pitches to accomplish and the movement style is less relevant. Moreover, alpinists make use of removable protections, hence the challenge of the environment is even greater, and a big part of the expertise also consists of the ability to put the protections in the rock. The sport culture is relevant for the design of wearable devices because it shapes the sport activity, i.e. the artefacts used to participate in the sport and the relationship the sportsperson has with the natural environment, as well as her/his own personal goals and sense of self-fulfilment (Daiber et al., 2016). Therefore, sport culture influences the likelihood of an outdoor sportsperson's acceptance of a wearable device to be used during the sport activity and informs the optimal level of intrusiveness or transparency of the technology, i.e. what role such device should have towards the sportsperson (e.g. enabler, support, substitute, etc.). Furthermore, literature on outdoors sports reports that there is a high difference between the role of technology during the usual practice training and in case of emergency or unexpected events. If in the first case the technology has to be in the background not to undermine the sense of self-efficacy of the sportsperson and taking roles of diary (Ahtinen et al., 2008; Müller & Pell, 2016; Cheverst et al., 2018) or facilitator of expertise communication as in the case study, in case of breakdown the technology should assume much more prominent roles (Desjardins et al., 2014; Müller & Pell, 2016). Overall, from the work reported in this thesis and previous HCI works in the same domain, it emerges that outdoor adventure sports are characterised by a strong cultural identity, which defines and justifies practices. Such sport culture should be considered in the design of wearable devices in order for the technology not to distort the practice, but to integrate to it.

The sport activity. The sport activity consists in the setting, the artefacts, the performance, the social dynamics and the procedures of the sport. In outdoor adventure sports, the natural environment is characterised by a prevalent spatial orientation (verticality vs. horizontality), different natural elements, and a certain level of immersiveness, which together contribute

[7] For the description of the *solo* climbing, see the Glossary in the Introduction.

to the challenges provided by different outdoor adventure sports. For example, skiing is characterised by the verticality of the mountain environment and snow but is not completely immersive since skiers interact with the surface of snow; speleology can be either vertical or horizontal and is characterised by immersive darkness; scuba diving is characterised by the complete immersion in water. According to the findings of fieldwork observations, the artefacts used in the sport practice can be classified as those *necessary* to the activity or those *auxiliary* to the activity. The necessary artefacts can be instrumental to the activity (e.g. the climbing shoes) or required for safety (e.g. the rope, the harness, a belay device, etc.). The auxiliary artefacts include those that facilitate better performance (e.g. chalk) or support the teaching activities (e.g. wooden cubes, the slackline, gloves, cloth bands, etc.). Another key element of the sport activity is the performance. It differs from sport to sport and can consist of endurance, speed, or the execution of precise and difficult movements. Finally, another crucial component of the sport activity is the social dynamics. Typically, in outdoor adventure sports the performance is individual but, nonetheless, the procedures involve more than one person for safety reasons. To fully understand how the sport activity unfolds, it is necessary to consider its level of sociality: is it conducted in pairs or in groups? What kind of relationship is established with the others? What kind of communication exchanges occur (functional or emotional, concrete or abstract)? Does the sport involve competition with rivals besides coordination and collaboration with the sport partners? What are the partners responsibility of for each other (e.g. wellbeing, safety, etc.)?

When designing wearables for outdoor adventure sports, it is important to consider the characteristics of the environment where the sport takes place because it influences the performance, the sportsperson's emotions, and the possibility to communicate with the sport partners. The more the sport requires participants to move in conditions that are distant from the usual motor patterns (like swimming underwater or climbing), the more the performance can be stressful. Moreover, the type of environment shapes the type of technology in terms of robustness and perceptibility of information for the wearer. For example, the technology for speleology should be based on lights, while a technology to be used on glaciers, where when the sunlight is strong the view is fatigued, should avoid screens. The nature of performance and the social dynamics influence the function of technology. In particular, the performance informs the parameters to set if the wearable is an activity tracker and the correspondent sensors and actuators, while the social dynamics opens up potential new relational functions of the wearable technology. In sum, the sport activity informs the purpose of the technology, the type of technology that can be used, and consequently its product design.

The sportsperson. Another aspect of the framework is the sportsperson and her/his level of engagement in the activity. As demonstrated by the case study and the literature, the engagement required by outdoor adventure sports to the practitioners is at the same time cognitive, emotional, and physical. All these aspects must be taken into consideration because they derive from the sport experience as a whole (Tholander & Nylander, 2015). Since these levels of engagement are closely linked and are continuous during the performance, it is important to investigate when the peaks in focus occur as well as the peaks in positive and negative emotions, alongside the bodily aspects of performance and its timing. The results of such investigations could help determine the optimal level of presence and intrusiveness of technology in every specific moment of the activity. Regarding the analysis of the physical engagement, the physical and the identification of the sportsperson's body parts and senses involved in the performance would influence the ergonomics of the wearable artefact.

The product design. The main goal of the product design of an artefact that has to be worn on the body its wearability. Wearability is the property that defines the extent to which an artefact is easily worn and depends on its comfort (Gemperle et al., 1998) and social acceptability (Dunne et al., 2014). Therefore, the principle of wearability affects the shape, the location on the body and the interaction modality of the artefact. The shape of the wearable device should depend on elements of ergonomics to adapt it to the forms of the human body in movement, and aesthetic considerations to meet the cultural values of the community. The product design of a wearable device should be influenced by its technological function (i.e. what the wearable has to do), the sport activity which informs of which body parts are involved, and the degree to which the device can signify or symbolise the ideal self that the sportsperson wants to express.

The technology. The technology aspect refers to the purpose, role, function and type of the technology used. The purpose of technology identifies what the wearable device aims to do, e.g. to improve the performance or to manage negative emotions. The purpose is therefore informed by the sport practice with its goals, types of performance, and sportspeople needs. Secondly, the role of technology identifies how the wearable positions itself and acts in relation to the sportsperson and is strongly influenced by the sport culture. For example, if the goal is to improve the performance, the role of the technology could be that of a virtual coach or of a system to augment the communication between coach and sportsperson, according to the level of experience of the sportsperson and to the importance of the interpersonal relation in the sport. Thirdly, the function of the technology defines how the wearable realises its purpose in practical terms, e.g. supporting the improvement of the performance by recording physiological data of the sportsperson or by recording a video of the whole performance. Finally, the type of technology identifies the hardware and the software (i.e. the choice of sensors, actuators, etc.) adopted. This choice is informed by the purpose of the technology itself, the activity required by the sport, and the sportsperson's body parts and sensorial channels involved in the action. It is worth noticing that, once the technology is introduced in the sport practice, the direction of influence is reversed: the use of technology will influence the sport practice.

Outdoor adventure sports differ from each other in terms of the settings where they take place, number of people involved, etc. By analysing and understanding the nature and the importance of these elements take in a specific sport, it is possible to design wearables that are useful, acceptable, and desirable by the people practising that sport.

SPORT ACTIVITY
• Settings
• Artefacts
• Performance
• Social dynamics
• Procedures
 	
informs the purpose and the type of technology, and the product design.
	SETTING: (In what kind of environment does it take place?)
	• Orientation & immersiveness
	  o horizontal (on the ground, on the water)?
	  o vertical (mountains, speleology, scuba-diving)?
	• How much adventurous the sport is?
	  o What natural elements are involved? Snow, sand, forests, darkness?
	  o What level of artificial intervention is there?
	• Indoor version (does the sport have an indoor equivalent? Is it used for training or is it a practice in itself?)
	
	ARTEFACTS: What kind of artefacts are used?
	• Necessary
	  o Instrumental to the activity
	  o For safety
	• Auxiliary
	  o For a better performance
	  o Teaching artefacts
	
	PERFORMANCE: What kind of performance is required? Speed / endurance / style / etc.?
	
	SOCIAL DYNAMICS: What level of sociality does the sport involve? And what kind of social dynamics does it involve?
	• Individual / pairs / groups
	• Relations with sport partners. Is there
	  o Communication? Of what kind (Functional vs. emotional, concrete vs. abstract)?
	  o Competition, Coordination, Collaboration, Trust
	  o Support of partner's safety & wellbeing
	PROCEDURES: rules and codified behaviours

<table>
<tr><td>SPORT CULTURE
Values
Myth
Community
influences the sport activity and the sportsperson and informs the likelihood of acceptance and the role of technology</td><td>VALUES that define motivation (why did you choose to practise this outdoor sport?), goal (what do you want to reach?), What expertise is required? How much technological support are you willing to receive?
Trade-off between adventure and safety
Self-efficacy and expertise
Pride and sense of belonging to the sport community (influence social acceptance)
MYTH: e.g. hard challenges, pioneers.

COMMUNITY: Is there a sense of identification and belonging?</td></tr>
<tr><td>SPORTSPERSON'S ENGAGEMENT
Mind
Emotions
Body
informs the ergonomics of the artefact and the type of technology allowed.</td><td>COGNITIVE: What kind of cognitive engagement does this sport require? When?
Focus
Strategy
EMOTIONAL: What kinds of emotions does this sport provoke? Are they collective or individual? What are the typical emotional states triggered by the sport?
Positive emotions: e.g. flow, satisfaction, shared happiness
Negative emotions: e.g. fear, stress, frustration
BODILY: What kind of bodily engagement does this sport require?
Kind of performance required
Body parts involved in the action
Senses involved in the action</td></tr>
<tr><td>TECHNOLOGY
Purpose
Role
Function
Type</td><td>PURPOSE
What kind of support should the wearable provide?
ROLE
How should the wearable support the sportsperson? Tanking the role of a coach, of a reminder, of an enabler, etc.?
FUNCTION
How does the technology realise the purpose of the device from a practical point of view? Does it monitor the activity? Does it send feedback?
TYPE
What kind of hardware and software is required?</td></tr>
<tr><td>PRODUCT DESIGN
Wearability
Ergonomics
Social acceptance</td><td>WEARABILITY
Is the device comfortable to wear?
ERGONOMICS
Does the device adapt to the shapes and the movements of the body?
SOCIAL ACCEPTANCE
Do the aesthetics, the interaction, and the location on the body guarantee the social acceptability of the wearer?</td></tr>
</table>

Table 8. A detailed scheme of the conceptual framework.

6.2.3 A Kit of Wearables for Augmenting Communication in Climbing

The third contribution of this thesis is a kit of wearables for augmenting interpersonal communication in climbing. This kit is intended to become a part of the set of auxiliary artefacts used by climbing instructors for teaching. This kit was the result of adopting a UCD approach to the problem of the design of wearable devices for sport, which has highlighted important elements of the sport practice not previously considered in design. In the case of climbing, this approach has made negative emotions, trust and values emerge as pivotal for the sport practice. Specifically, through the UCD approach three pivotal features of the climbing practice have been identified: the values held by climbers regarding their sport and the use of technology in it; the influence of negative emotions on the success of the performance; and the importance of interpersonal trust. These elements have been considered in the design process. Crucially, the system design reflects users' preferences on what kind of technology, aid, and role are acceptable in their community accordingly to their sport values and aims to help climbers to harness their negative emotions and to develop trust.

Following the findings of the fieldwork, a wearable device was developed for augmenting the interpersonal communication from the climbing instructor to the beginner through vibration. The system leaves instructors in charge of assessing the situation and making decisions about whether to send feedback, thus respecting their expertise as climbers and as teachers. The evaluation of the probe took place in the real-life context of a climbing lesson and showed that the decision to give the instructors control over the sending of vibrations led to several advantages: climbers' flow was not interrupted too often, their cognitive load was kept low, and they were allowed to try different movements on their own, thus not becoming dependent on the feedback. Furthermore, by bringing beginner climbers' attention to specific parts of the body, the wearable device helps them to become aware of invisible physical mechanisms such as the relationship between balance and the changes in the centre of gravity, thus developing self-awareness and proprioception. Moreover, as a means of augmented interpersonal communication, the vibration promotes a sense of safety in beginner climbers by making them feel the instructor's attentive presence and is perceived by beginner climbers as reliable because an expert person directs it. Finally, the expressive ambiguity of vibration was perceived as an openness that enabled negotiations of meanings between the instructor and the trainee and adaptation of the device to different learning purposes, possibly paving the way for appropriation (Gaver, Beaver, & Benford, 2003).

The work presented in this thesis has shown that by adopting a User Centred Design (UCD) approach, i.e. basing the design on users' needs and values, it is possible to gain new perspectives on the role of wearables for sport, shifting the focus from activity tracking to a support for the sharing of expertise. Specifically, the design process described here has led to the design and development of wearable devices that bridge the communication gap in climbing by providing an augmented communication system that addresses both the functional and emotional aspects. Unlike the previous works on wearable technology in climbing, this new wearable kit does not aim merely at enhancing the body through the awareness of its performance, but the whole person, considering her body, emotions, and relations to the other actors involved.

07 Conclusion

7. Conclusion

This chapter presents a summary of the thesis, some personal reflections by the author, and suggestions about the possible limitations and future directions of the research work presented.

7.1 Summary

Nowadays, wearable devices are an increasingly popular technology, but their actual adoption is often short-lived. This thesis presented a research process aimed at mapping the design space of acceptable, desirable, and useful wearable devices for climbing starting from a thorough understanding of the sport practice. By adopting a methodology based on situatedness and embodiment and a co-design approach, it was possible to gain a new perspective on the sport practice, which highlighted the relevance of emotions and values in sport besides the performance. Indeed, the findings showed that learning to climb is not just a matter of acquiring new motor skills, but it also requires the building of trust in the belayer and the ability to control negative emotions. During the climbing learning process, positive and negative emotions alternate and the communication between the actors involved plays an important role in promoting a positive experience. Moreover, findings showed that there are strong values in the climbers' community, which influence individual's opinion on the purpose and the role that technology should have in order to be welcomed in their sport. It emerged that great importance is given to people being competent in what they are doing, and technology should not replace their expertise, but rather help conveying it to their partners. Therefore, to be adopted and used, wearable devices should help climbers reflect, communicate, coordinate, and trust their partner.

A co-design workshop was conducted to explore the potentialities of wearable devices to address climbers' needs and values. Out of this workshop emerged a series of concepts focused on increasing the awareness of the actors involved on the invisible physical phenomena of climbing and enabling distance communication among them. Due to the likely cognitive tension of the climber, in the emergent concepts the preferred communication modality was haptics. These findings led to an exploration of the technology for haptic feedback currently available on the market and a comparison of the different feedback modalities to find the more appropriate one to the climbing context. In the end, vibration was preferred, as it can be easily modulated and is low in energy consumption. A second co-design workshop was conducted to explore the possible way to exploit vibration for communication in climbing, and different configurations were elaborated for conveying different meanings.

The results of the design phase converged in the design and building of a wearable system composed of a series of bands enhanced with vibrating motors and a tablet interface to control them. This system was intended to enable the instructor to send vibrations to the climber while s/he was actually on the wall. It was evaluated as a technological probe to investigate the perceived usefulness, preferred location(s) on the body, and the effects of the vibrations on the climber in a real-life climbing context. The results of the evaluation showed that climbers felt reassured knowing that help could be communicated to them, despite the vibration sometimes caught them by surprise. Both the beginner climbers and the instructor valued the opportunity to receive/provide a 'nudge' in real time and the adaptability of the system to the needs of the moment, i.e. the possibility to use vibration as a feedback or as an instruction. These findings, together with the climbers' preference to wear the devices on the abdomen and at the ends of the limbs, paved the way for the design of a kit of auxiliary wearables to adopt when needed and adapt to the purpose of a particular moment.

7.2 Personal Reflections

The need for sensorial empathy. Is it possible to investigate and design artefacts for a sport without practising it? In my view, it is possible, but it brings a high risk of deficits in understanding. If the researcher is not a practitioner of that sport, s/he would miss the sensorial empathy needed to fully understand of what that sport requires, and it would be harder to have an empathic dialogue with those who practice the sport. My personal experience of being a climber, and especially a beginner climber, has given me a certain sensitivity towards the themes raised by the interviewees. The benefit of experiencing first-hand the sensations provided by climbing and especially the inextricable links between the physical and mental aspects of climbing was reflected also in the embodied activities during the workshop in the climbing gym. As in all the domains where researchers do not have direct, personal experience, in my view it would be extremely helpful to develop research methods capable of capturing and reporting participants' subjective emotional states and physical sensations that characterise the sport experience.

Personal reflections on the method. This thesis was based on qualitative methods, which took into account the situated and material aspects of the sport domain, as well as the importance of involving the user in the design process. Nevertheless, my awareness of the necessity to recreate an immersive experience and an empathic situation in the design phase has strengthened during the research process itself. Indeed, reflecting on the workshops, I acknowledge an increase of the level of situatedness, embodiment, and co-creation in the second one. While the first workshop was conducted with participants who owned both types of expertise needed (i.e. designers with personal experience of outdoor sports in the mountains), the second one brought together designers and climbers in a climbing gym and let them experience first the sensations of climbing and then proceed to the design activity on-site. This second arrangement has led to the generation of concepts that were arguably less imaginative but significantly more pragmatic because it allowed the participants to pay more attention to the aspects of interaction, such as the difficulty of providing manual input to a device while the hands are occupied grasping holds or holding the rope. The importance of the tangibility and materiality of the experience is reflected by the example of the felt pads during the second co-design workshop. The use of felt pads spontaneously generated a specific form of bodystorming that one of the participants named *fingerstorming*; it consisted of applying pressure with the finger tips on specific parts of the body, with different intensities and rhythms to simulate the different possible sequences of vibration. This way of working is very informative, but also very expensive in terms of resources, time, and energy. Indeed, the second workshop lasted many hours and in order to be at the same time the facilitator of the workshop and to collect data, I needed the support of two collaborators. Therefore, I think it would be interesting and desirable to investigate the research practice of workshops in order to understand the elements that constitute them and the dynamics of collaboration. A reflection on the workshop methodology that would account for its sequencing, environments and materials in relation to its purpose, either it being inspirational, explorative, or oriented to a decision-making, would allow them to be more efficient and effective in providing on the one hand useful insight for the researchers and, on the other hand, enriching experience for participants.

7.3 Limitations & Future work

The work presented in this thesis presents some limitations, which are meant to be addressed with future work. In following paragraphs, the limitations are listed according to the three contributions of the thesis.

From a methodological point of view, one arguable limitation of this work is that this thesis has the limit to present studies on an outdoor sport (i.e. climbing) conducted in the indoor context, which entailed the loss of some environmental aspects of the climbing experience and might have caused the non-emergence of some important insights. Moreover, the majority of participants engaged in the studies changed along the research process. The only recurring participants have been a girl who took part in one of the focus groups and in both the co-design workshops since she is at the same time a climber as well as a designer, and a designer who took part in both the co-design workshops.

Regarding the framework, another possible limitation of this work is that it is based on a unique case study, that of climbing, while generalising to outdoor adventure sports in general. The analysis of more outdoor adventure sports would have potentially strengthened the robustness of the conceptual framework, which currently relies on the study of the literature. However, it is already planned to validate it with other outdoor adventure sports during a two-year fellowship that the author has obtained. Moreover, it is worth noticing that the conceptual framework allows for further extension of its categories to encompass the design of wearable devices for sports other than the outdoor ones. For example, in the case of team sports, the 'social dynamics' category would need to be extended in order to explain the internal dynamics of teams (e.g. hierarchy, roles, etc.), as well as the dynamics of the real-time competition with the opposing team in the presence of a referee.

Regarding the prototype for climbing, its logical developments would be an evaluation in the outdoor environment in order to verify its usefulness and acceptability also in that context, and the implementation of an interface for the instructor that does not require too much visual attention (e.g. a tangible interface that could be recognised through touch) and provides him with a feedback that the vibration has been sent. Further work could then be done to develop a vocabulary of vibrations in order to investigate whether vibration could be used to convey encoded meanings and whether these would also be understood by the climber in situations of high cognitive load such as when being stressed or scared, and to look at the effects of communication about emotional states separated from communication about movements. Finally, a long-term study to investigate adoption of the new wearable device, and not only the initial acceptance. The prototype presented in this thesis and its evaluation can be considered as the testing of the 'minimum viable product' for then considering the production of a commercial system or the implementation of a functionality for augmented interpersonal communication in already existing wearables for sports. In the future, the commercialisation of the prototype will be considered by involving established companies in the section of outdoor gear and apparel.

Bibliography

Aggravi, M., Salvietti, G., & Prattichizzo, D. (2016). Haptic Assistive Bracelets for Blind Skier Guidance. In *Proceedings of the 7th Augmented Human International Conference* (pp. 1–4). ACM Press. https://doi.org/10.1145/2875194.2875249

Ahtinen, A., Huuskonen, P., & Häkkilä, J. (2010). Let's All Get Up and Walk to the North Pole: Design and Evaluation of a Mobile Wellness Application. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: extending boundaries* (pp. 3–12). ACM. Retrieved from http://portal.acm.org/citation.cfm?id=1868914&coll

Ahtinen, A., Isomursu, M., Huhtala, Ykä, Kaasinen, J., Salminen, J., & Häkkilä, J. (2008). Tracking Outdoor Sports - User Experience Perspective. *European Conference on Ambient Intelligence*, 192–209.

Ahtinen, A., Isomursu, M., Mukhtar, M., Mäntyjärvi, J., Häkkilä, J., & Blom, J. (2009). Designing social features for mobile and ubiquitous wellness applications. In *Proceedings of the 8th international Conference on Mobile and Ubiquitous Multimedia*. ACM Press. https://doi.org/10.1145/1658550.1658562

Alhonsuo, M., Hapuli, J., Virtanen, L., Colley, A., & Häkkilä, J. (2015). Concepting Wearables for Ice-Hockey Youth (pp. 944–946). ACM Press. https://doi.org/10.1145/2786567.2794315

Bächlin, M., Förster, K., & Tröster, G. (2009). SwimMaster: a wearable assistant for swimmer. In *Proceedings of the 11th International Conference on Ubiquitous Computing* (pp. 215–224). https://doi.org/10.1145/1620545.1620578

Bannon, L. J. (1992). From human factors to human actors: the role of psychology and human-computer interaction studies in system design. In J. Greenbaum & M. Kyng (Eds.), *Design at work: cooperative design of computer systems*. L. Erlbaum Associates Inc.

Basdogan, C., Ho, C., Srinivasan, M. A., & Slater, M. E. L. (2000). An Experimental Study on the Role of Touch in Shared Virtual Environments. *ACM Transactions on Computer-Human Interaction*, *7*(4), 443–460.

Berg, B. L., & Lune, H. (2014). *Qualitative research methods for the social sciences* (8th ed.). Pearson Education Limited.

Beyer, H., & Holtzblatt, K. (2009). *Contextual design: defining customer-centered systems* (Repr.). San Francisco, Calif.: Morgan Kaufmann.

Bial, D., Appelmann, T., Rukzio, E., & Schmidt, A. (2011). Improving Cyclists Training with Tactile Feedback on Feet. In *Proceedings of the 7th international Conference on Haptic and Audio Interaction Design*.

Bødker, S. (2006). When second wave HCI meets third wave challenges. In *Proceedings of the 4th Nordic Conference on Human-Computer Interaction* (pp. 1–8). ACM Press. https://doi.org/10.1145/1182475.1182476

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Brave, S., & Dahley, A. (1997). inTouch: a Medium for Haptic Interpersonal Communication. In *Extended Abstracts on Human Factors in Computing Systems - CHI EA'97* (pp. 363–364). Retrieved from http://dl.acm.org/citation.cfm?id=1120435

Brewster, S. A., & Brown, L. M. (2004). Tactons: Structured Tactile Messages for Non-Visual Information Display. In *Proceedings of the 5th Australasian User Interface Conference - AUIC* (pp. 15–23).

Brewster, S., Chohan, F., & Brown, L. (2007). Tactile Feedback for Mobile Interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 159–162). New York, NY, USA: ACM. https://doi.org/10.1145/1240624.1240649

Brymer, E., & Gray, T. (2009). Dancing with nature: Rhythm and Harmony in Extreme Sport Participation. *Journal of Adventure Education & Outdoor Learning*, *9*(2), 135–149.

Brymer, E., & Schweitzer, R. (2012). Extreme sports are good for your health: A phenomenological understanding of fear and anxiety in extreme sport. *Journal of Health Psychology*. https://doi.org/10.1177/1359105312446770

Byrne, R., & Müller, F. 'Floyd'. (2014). Designing Digital Climbing Experiences through Understanding Rock Climbing Motivation. In *Entertainment Computing – ICEC'14* (pp. 92–99).

Canhoto, A. I., & Arp, S. (2017). Exploring the factors that support adoption and sustained use of health and fitness wearables. *Journal of Marketing Management*, *33*(1–2), 32–60. https://doi.org/10.1080/0267257X.2016.1234505

Carbon, C.-C., & Jakesch, M. (2013). A Model for Haptic Aesthetic Processing and Its Implications for Design. *Proceedings of the IEEE*, *101*(9), 2123–2133. https://doi.org/10.1109/JPROC.2012.2219831

Carrington, P., Chang, K., Mentis, H., & Hurst, A. (2015). 'But, I don't take steps': Examining the Inaccessibility of Fitness Trackers for Wheelchair Athletes. In *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility* (pp. 193–201). ACM Press. https://doi.org/10.1145/2700648.2809845

Caspersen, C. J., Powell, K. E., & Christenson, G. M. (1985). *Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research* (Public health reports No. 100(2)) (p. 126).

Cauchard, J. R., Cheng, J. L., Pietrzak, T., & Landay, J. A. (2016). ActiVibe: Design and Evaluation of Vibrations for Progress Monitoring. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (pp. 3261–3271). https://doi.org/10.1145/2858036.2858046

Cheverst, K., Bødker, M., & Daiber, F. (2018). Technology and Mastery: Exploring Design Sensitivities for Technology in Mountaineering. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'18* (p. 5).

Choi, W., Oh, J., Edge, D., Kim, J., & Lee, U. (2016). SwimTrain: Exploring Exergame Design for Group Fitness Swimming. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16* (pp. 1692–1704). https://doi.org/10.1145/2858036.2858579

Climbing Grades. (n.d.). Retrieved 17 September 2016, from https://en.wikipedia.org/wiki/Grade_(climbing)

Colley, A., & Häkkilä, J. (2017). Hedonic Design for Winter UbiMount – Illuminated Snowboard In-the-Wild. In *Proceedings of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and International Symposium on Wearable Computers* (pp. 1027–1032).

Colley, A., Väyrynen, J., & Häkkilä, J. (2015). Skiing in a blended virtuality: an in-the-wild experiment (pp. 89–91). ACM Press. https://doi.org/10.1145/2818187.2818288

Consolvo, S., Everitt, K., Smith, I., & Landay, J. A. (2006). Design Requirements for Technologies that Encourage Physical Activity. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (pp. 457–466). ACM.

Consolvo, S., Klasnja, P., McDonald, D. W., Avrahami, D., Froehlich, J., LeGrand, L., ... Landay, J. A. (2008). Flowers or a robot army?: encouraging awareness & activity with personal, mobile displays. In *Proceedings of the 10th international conference on Ubiquitous computing* (pp. 54–63). ACM Press. https://doi.org/10.1145/1409635.1409644

Curmi, F., Ferrario, M. A., & Whittle, J. (2017). Biometric data sharing in the wild: Investigating the effects on online sports spectators. *International Journal of Human-Computer Studies*, *105*, 56–67. https://doi.org/10.1016/j.ijhcs.2017.03.008

Daiber, F., Kosmalla, F., & Krüger, A. (2013). BouldAR – Using Augmented Reality to Support Collaborative Boulder Training Abstract. In *Extended Abstracts on Human Factors in Computing Systems - CHI EA'13* (pp. 949–954).

Daiber, F., Kosmalla, F., Wiehr, F., & Krüger, A. (2016). Outdoor Nature Lovers vs. Indoor Training Enthusiasts: A Survey of Technology Acceptance of Climbers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'16*.

Desjardins, A., Neustaedter, C., Greenberg, S., & Wakkary, R. (2014). Collaboration Surrounding Beacon Use During Companion Avalanche Rescue. In *Proceedings of the 17th ACM conference on Computer Supported Cooperative Work & Social Computing - CSCW'14* (pp. 877–887). https://doi.org/10.1145/2531602.2531684

Dourish, P. (2004). *Where the Action is: the Foundations of Embodied Interaction*. The MIT Press.

Dufour, T., Pellarrey, V., Chagnon, P., Majdoubi, A., Torregrossa, T., Bachbaur, V., ... Dumas, F. (2014). ASCENT: A First Person Mountain Climbing Game on the Oculus Rift. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'14* (pp. 335–338).

Dundee Degree Show. (2011). Retrieved from https://www.dundee.ac.uk/djcad/degreeshow2011/studentsexhibiting/productdesign/malcolm_russell/

Dunne, L. E., Profita, H., Zeagler, C., Clawson, J., Gilliland, S., Do, E., & Budd, J. (2014). The social comfort of wearable technology and gestural interaction. In *Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 4159–4162). https://doi.org/10.1109/EMBC.2014.6944540

Dutkiewicz, J. (2014). Pretzel Logic: An Embodied Ethnography of a Rock Climb. *Space and Culture*, *18*, 25–38. https://doi.org/10.1177/1206331214532044

Ericsson Consumerlab. (2016). *Wearable technology and Internet of things* (pp. 1–22). Retrieved from https://www.ericsson.com/res/docs/2016/consumerlab/wearable-technology-and-the-internet-of-things-ericsson-consumerlab-2016.pdf

Fedosov, A., Niforatos, E., Elhart, I., Schneider, T., Anisimov, D., & Langheinrich, M. (2016). Design and Evaluation of a Wearable AR System for Sharing Personalized Content on Ski Resort Maps. In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia (MUM'16)*. (pp. 141–152).

Feeken, C., Wasmann, M., Heuten, W., Ennenga, D., Müller, H., & Boll, S. (2016). ClimbingAssist – Direct Vibro-Tactile Feedback on Climbing Technique. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct.* (pp. 57–60).

Feygin, D., Keehner, M., & Tendick, F. (2002). Haptic Guidance: Experimental Evaluation of a Haptic Training Method for a Perceptual Motor Skill. In *Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002* (pp. 40–47).

Fiorentino, M., Uva, A., Foglia, M., & Bevilacqua, V. (2013). Asymmetry measurement for vibroactive correction in lower limbs mobility. *Computer Science and Information Systems*, *10*(3), 1387–1406. https://doi.org/10.2298/CSIS120516054F

Fogtmann, M. H., Fritsch, J., & Kortbek, K. J. (2008). Kinesthetic Interaction - Revealing the Bodily Potential in Interaction Design. In *Proceedings of the 20th Australasian Conference on Computer-Human Interaction* (pp. 89–96). https://doi.org/10.1145/1517744.1517770

Fogtmann, M. H., Grønb\a ek, K., & Ludvigsen, M. K. (2011). Interaction technology for collective and psychomotor training in sports. In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology - ACE'11.* New York, New York, USA: ACM Press. https://doi.org/10.1145/2071423.2071440

Franke, T., Pieringer, C., & Lukowicz, P. (2011). How should a wearable rowing trainer look like? A user study. In *Proceedings of the 15th Annual International Symposium on Wearable Computers* (pp. 15–18). https://doi.org/10.1109/ISWC.2011.15

Friedman, B. (1996). Value-sensitive design. *Interactions*, *3*(6), 16–23. https://doi.org/10.1145/242485.242493

Gardner, T. (2015). *Popularity and economic benefit of mountaineering: instant expert.* Retrieved from https://www.thebmc.co.uk/participation-in-climbing-mountaineering

Gaver, W. W., Beaver, J., & Benford, S. (2003). Ambiguity as a resource for design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'03* (p. 233). ACM Press. https://doi.org/10.1145/642611.642653

Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M., & Martin, R. (1998). Design for wearability. In *Proceedings of the 2nd International Symposium on Wearable Computers* (pp. 116–122). https://doi.org/10.1109/ISWC.1998.729537

Goodman, E., Kuniavsky, M., & Moed, A. (2012). *Observing the User Experience: A Practicionner's Guide to User Research* (Second). Morgan Kauffman.

Gouveia, R., Barros, S., & Karapanos, E. (2014). Understanding users' disengagement with wearable activity trackers. In *Proceedings of the 2014 Workshops on Advances in Computer Entertainment Conference - ACE '14 Workshops* (pp. 1–3). https://doi.org/10.1145/2693787.2693802

Hale, K. S., & Stanney, K. M. (2004). Deriving Haptic Design Guidelines from Human Physiological, Psychophysical, and Neurological Foundations. *IEEE Transactions on Computer Graphics and Applications*, *24*(2), 33–39.

Hanin, Y. L. (2007). Emotions in Sport: Current Issues and Perspectives. In G. Tenenbaum & R. C. Eklund (Eds.), *Handbook of Sport Psychology* (pp. 31–58). Hoboken, NJ: John Wiley & Sons. https://doi.org/10.1002/9781118270011.ch2

Harrison, C., Lim, B. Y., Shick, A., & Hudson, S. E. (2009). Where to Locate Wearable Displays? Reaction Time Performance of Visual Alerts from Tip to Toe. In

Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'09 (pp. 941–944). https://doi.org/10.1145/1518701.1518845

Harrison, S., Tatar, D., & Sengers, P. (2007). The three paradigms of HCI. In *Alt. Chi. Session at the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1–18).

Hasegawa, S., Ishijima, S., Kato, F., Mitake, H., & Sato, M. (2012). Realtime Sonification of the Center of Gravity for Skiing. In *Proceedings of the 2012 Augmented Human International Conference* (pp. 3–6). https://doi.org/10.1145/2160125.2160136

Havlucu, H., Bostan, I., Coskun, A., & Özcan, Ö. (2017). Understanding the Lonesome Tennis Players: Insights for Future Wearables. In *Extended Abstracts on Human Factors in Computing Systems - CHI EA'17* (pp. 1678–1685). ACM.

Huisman, G., Darriba Frederiks, A., Van Dijk, B., Hevlen, D., & Krose, B. (2013). The TaSSt: Tactile sleeve for social touch. In *World Haptics Conference - WHC'13* (pp. 211–216). https://doi.org/10.1109/WHC.2013.6548410

Hutchinson, H., Hansen, H., Roussel, N., Eiderbäck, B., Mackay, W., Westerlund, B., ... Evans, H. (2003). Technology probes: inspiring design for and with families. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (p. 17). ACM Press. https://doi.org/10.1145/642611.642616

Jensen, M. M., Rasmussen, M. K., & Grønb\a ek, K. (2014). Design Sensitivities for Interactive Sport-Training Games. In *Proceedings of the ACM Conference on Designing Interactive Systems - DIS'14* (pp. 685–694).

Kajastila, R., Holsti, L., & Hämäläinen, P. (2016). The Augmented Climbing Wall: High-Exertion Proximity Interaction on a Wall-Sized Interactive Surface. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (pp. 758–769). New York, NY, USA: ACM. https://doi.org/10.1145/2858036.2858450

Karapanos, E., Gouveia, R., Hassenzahl, M., & Forlizzi, J. (2016). Wellbeing in the Making: People's Experiences with Wearable Activity Trackers. *Psychology of Well-Being*, *6*(1), 1–17. https://doi.org/10.1186/s13612-016-0042-6

Knaving, K., Woźniak, P. W., Fjeld, M., & Björk, S. (2015). Flow is Not Enough: Understanding the Needs of Advanced Amateur Runners to Design Motivation Technology. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 2013–2022).

Kosmalla, F., Daiber, F., & Krüger, A. (2015). ClimbSense - Automatic Climbing Route Recognition using Wrist-worn Inertia Measurement Units. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'15* (pp. 2033–2042).

Kosmalla, F., Wiehr, F., Daiber, F., Krüger, A., & Löchtefeld, M. (2016). ClimbAware - Investigating Perception and Acceptance of Wearables in Rock Climbing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'16*.

Kosmalla, F., Zenner, A., Speicher, M., Daiber, F., Herbig, N., & Krüger, A. (2017). Exploring Rock Climbing in Mixed Reality Environments (pp. 1787–1793). ACM Press. https://doi.org/10.1145/3027063.3053110

Kuutti, K., & Bannon, L. J. (2014). The turn to practice in HCI. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14* (pp. 3543–3552). https://doi.org/10.1145/2556288.2557111

Ladha, C., Hammerla, N. Y., Olivier, P., & Plötz, T. (2013). ClimbAX: Skill Assessment for Climbing Enthusiasts. In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (pp. 235–244). ACM.

Lappalainen, T., Virtanen, L., & Häkkilä, J. (2016). Experiences with Wellness Ring and Bracelet Form Factor. In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia* (pp. 351–353). ACM. https://doi.org/10.1145/3012709.3016065

Lauber, B., & Keller, M. (2012). Improving motor performance: Selected aspects of augmented feedback in exercise and health. *European Journal of Sport Science*, *14*(1), 36–43. https://doi.org/10.1080/17461391.2012.725104

Lazar, A., Koehler, C., Tanenbaum, J., & Nguyen, D. H. (2015). Why we use and abandon smart devices. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp'15* (pp. 635–646). https://doi.org/10.1145/2750858.2804288

Ledger, D., & McCaffrey, D. (2014). Inside wearables: How the science of human behavior change offers the secret to long-term engagement. *Endeavour Partners*, *200*(93). Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=96736583&site=ehost-live&scope=site

Levenhagen, M. (2010). A Stage Model of Why Climbers Climb And How It Frames the Discussions of Recent Climbing Controversies. *Journal of Mountaineering*, 16–33.

Lewis, N. (2000). The Climbing Body, Nature and the Experience of Modernity. *Journal of Body and Society*, *6*(10), 58–80. https://doi.org/0803973233

Lieberman, J., & Breazeal, C. (2007). TIKL: Development of a Wearable Vibrotactile Feedback Suit for Improved Human Motor Learning. *IEEE Transactions on Robotics*, *23*(5), 919–926.

Liljedahl, M., Lindberg, S., & Berg, J. (2005). Digiwall - an Interactive Climbing Wall. In *Proceedings of the 2005 ACM SIGCHI International Conference on Advances in computer entertainment technology* (pp. 225–228).

Lockton, D., Harrison, D., & Stanton, N. A. (2010). The Design with Intent Method: A design tool for influencing user behaviour. *Applied Ergonomics*, *41*(3), 382–392. https://doi.org/10.1016/j.apergo.2009.09.001

MacAloon, J., Csikszentmihalyi, M., Harris, J. C., & Park, R. J. (1983). Deep Play and the Flow Experience in Rock Climbing. In J. C. Harris & R. J. Park (Eds.), *Play, games and sports in cultural contexts* (pp. 361–384).

Mann, S. (1997). Wearable computing: A first step toward personal imaging. *Computer*, *30*(2), 25–32. https://doi.org/10.1109/2.566147

Mann, S. (1998). Wearable computing as a means for personal empowerment. In *Keynote Address for The First International Conference on Wearable Computing - ICWC'98*.

Marti, P. (2010). Perceiving while being perceived. *International Journal of Design*, *4*(2).

Mauriello, M., Gubbels, M., & Froehlich, J. E. (2014). Social Fabric Fitness: The Design and Evaluation of Wearable E-Textile Displays to Support Group Running. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'14* (pp. 2833–2842). https://doi.org/10.1145/2556288.2557299

Mononen, K. (2007). *The Effects of Augmented Feedback on Motor Skill Learning in Shooting: a Feedback Training Intervention among Inexperienced Rifle Shooters*. University of Jyväskylä, Jyväskylä.

Morris, D., Hong, T., Barbagli, F., Chang, T., & Salisbury, K. (2007). Haptic Feedback Enhances Force Skill Learning. In *World Haptics Conference - WHC'07* (pp. 21–26). IEEE.

Motamedi, N. (2007). The aesthetics of touch in interaction design. In *Proceedings of the Conference on Designing Pleasurable Products and Interfaces* (p. 455). ACM Press. https://doi.org/10.1145/1314161.1314205

Motti Genaro, V., & Caine, K. (2014). Human Factors Considerations in the Design of Wearable Devices. In *Proceedings of the Human Factors and Ergonomics Society 58th Annual Meeting* (pp. 1820–1824). https://doi.org/10.1177/1541931214581381

Müller, F. 'Floyd', Edge, D., Vetere, F., Gibbs, M. R., Agamanolis, S., Bongers, B., & Sheridan, J. G. (2011). Designing sports: a framework for exertion games. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'11* (pp. 2651–2660). https://doi.org/10.1145/1978942.1979330

Müller, F. 'Floyd', O'Brien, S., & Thorogood, A. (2007). Jogging over a Distance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'07* (pp. 1989–1994). https://doi.org/10.1145/1240866.1241045

Müller, F. 'Floyd', & Pell, S. J. (2016). Technology meets Adventure: Learnings from an Earthquake-Interrupted Mt. Everest Expedition. In *UbiComp* (pp. 817–828).

Nakamura, A., Tabata, S., Ueda, T., Kiyofuji, S., & Kuno, Y. (2005). Multimodal presentation method for a dance training system. In *Extended Abstracts on Human Factors in Computing Systems - CHI EA'05* (pp. 1685–1688). https://doi.org/10.1145/1056808.1056997

Nurkka, P. (2016). Customization in Long-term Use: The Case of the Sports Watch. In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia* (pp. 5–10). New York, NY, USA: ACM. https://doi.org/10.1145/3012709.3012744

Nylander, S., Tholander, J., Müller, F. 'Floyd', & Marshall, J. (2015). Hci and Sports. *Interactions*, 30–31. https://doi.org/10.1145/2729712

Oakley, I., McGee, M. R., Brewster, S. A., & Gray, P. (2000). Putting the Feel in 'Look and Feel'". In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'00* (pp. 415–422). ACM.

Page, M., & Vande Moere, A. (2007). Evaluating a Wearable Display Jersey for Augmenting Team Sports Awareness. In *Proceedings of the 5th International Conference on Pervasive Computing - PERVASIVE'07* (pp. 91–108). Springer-Verlag. https://doi.org/10.1007/978-3-540-72037-9

Pakanen, M., Lappalainen, T., Roinesalo, P., & Häkkilä, J. (2016). Exploring Smart Handbag Concepts through Co-Design. In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia* (pp. 37–48). ACM.

Pansiot, J., King, R. C., McIlwraith, D. G., Lo, B. P. L., & Yang, G. Z. (2008). ClimBSN: Climber performance monitoring with BSN. In *Proceedings of the 5th International Workshop on Wearable and Implantable Body Sensor Networks - BSN2008* (pp. 33–36). https://doi.org/10.1109/ISSMDBS.2008.4575009

Patel, M., & O'Kane, A. A. (2015). Contextual Influences on the Use and Non-Use of Digital Technology While Exercising at the Gym. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 2923–2932).

Pavel, D., Callaghan, V., & Dey, A. K. (2012). Supporting wellbeing through improving interactions and understanding in self- monitoring systems. In *Handbook of Ambient Assisted Living* (Vol. 11, pp. 408–433).

Phillips, E., Farrow, D., Ball, K., & Helmer, R. (2013). Harnessing and understanding feedback technology in applied settings. *Sports Medicine*, *43*, 919–925. https://doi.org/10.1007/s40279-013-0072-7

Pike, E. C. J., & Beames, S. K. (2013). *Outdoor Adventure and Social Theory*. Routledge.

Preece, J., Rogers, Y., & Sharp, H. (2015). *Interaction design: beyond human-computer interaction* (Fourth edition). Chichester: Wiley.

Rantakari, J., Inget, V., Colley, A., & Häkkilä, J. (2016). Charting design preferences on wellness wearables. In *Proceedings of the 7th Augmented Human International Conference 2016* (p. 28). ACM.

Rapp, A., & Cena, F. (2015). Affordances for Self-tracking Wearable Devices. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers* (pp. 141–142). https://doi.org/10.1145/2802083.2802090

Rogers, Y. (2011). Interaction design gone wild. *Interactions*, *18*(4), 58. https://doi.org/10.1145/1978822.1978834

Russell, J. A. (1980). A Circumplex Model of Affect. *Journal of Personality and Social Psychology*, *39*(6), 1161–1178. https://doi.org/10.1037/h0077714

Sallnäs, E.-L., Rassmus-Gröhn, K., & Sjöström, C. (2000). Supporting Presence in Collaborative Environments by Haptic Force Feedback. *ACM Transactions on Computer-Human Interaction*, *7*(4), 461–476.

Sanders, E. B.-N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign - International Journal of CoCreation in Design and the Arts*, *4*(1), 5–18. https://doi.org/10.1080/15710880701875068

Schleicher, D., Jones, P., & Kachur, O. (2010). Bodystorming as embodied designing. *Interactions*, *17*(6), 47. https://doi.org/10.1145/1865245.1865256

Schmid, A., Kleemann, M., Merritt, T., & Selker, T. (2015). Tactile Communication in Extreme Contexts: Exploring the Design Space through Kiteboarding. In *Human-Computer Interaction - INTERACT'15* (Vol. 1, pp. 37–54). https://doi.org/10.1007/978-3-319-22723-8

Schmidt, R. A., & Lee, T. D. (2011). *Motor Control and Learning. A Behavioral Emphasis*. Human Kinetics.

Schöning, J., Panov, I., & Kessler, C. (2007). No vertical limit - Conceptual LBS design for climbers. In *Extended Abstracts on Human Factors in Computing Systems - CHI EA'07* (pp. 1–5).

Shih, P. C., Han, K., Poole, E. S., Rosson, M. B., & Carroll, J. M. (2015). Use and Adoption Challenges of Wearable Activity Trackers. In *iConference Proceedings* (pp. 1–12).

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychonomic Bulletin & Review*, *20*(1), 21–53. https://doi.org/10.3758/s13423-012-0333-8

Simonsen, J., & Robertson, T. (2012). Participatory Design: an introduction. In *Routledge international handbook of participatory design* (pp. 21–38). Routledge.

Spelmezan, D. (2012). An investigation into the use of tactile instructions in snowboarding. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services - MobileHCI'12*. ACM Press. Retrieved from http://dl.acm.org/citation.cfm?doid=2371574.2371639

Stewart, C., Traitor, P., & Hanson, V. L. (2014). I'd Tap That! Providing Real Time Feedback on Roller Derby Skills.

Tholander, J., & Johansson, C. (2010). Design qualities for whole body interaction - Learning from Golf, Skateboarding and BodyBugging. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries - NordiCHI'10* (p. 493). https://doi.org/10.1145/1868914.1868970

Tholander, J., & Nylander, S. (2015). Snot, Sweat, Pain, Mud, and Snow: Performance and Experience in the Use of Sports Watches. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'15* (pp. 2913–2922). https://doi.org/10.1145/2702123.2702482

Tomico, O., & Wilde, D. (2015). Soft, Embodied, Situated & Connected. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct* (pp. 1179–1186).

Tomico, O., & Wilde, D. (2016). Soft, embodied, situated & connected: enriching interactions with soft wearables. *MUX: The Journal of Mobile User Experience*, *5*(1), 3. https://doi.org/10.1186/s13678-016-0006-z

Tomitsch, M., Aigner, W., & Grechenig, T. (2007). A concept to support seamless spectator participation in sports events based on wearable motion sensors. In *2nd International Conference on Pervasive Computing and Applications - ICPCA'07* (pp. 209–214). https://doi.org/10.1109/ICPCA.2007.4365441

Väänänen-Vainio-Mattila, K., Häkkilä, J., Karukka, M., & Kytökorpi, K. (2012). Exploring Non-verbal Communication of Presence between Young Children and Their Parents through the Embodied Teddy Bear. In *Ambient Intelligence* (Vol. 7683, pp. 81–96). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-34898-3_6

Vallerand, R. J., & Blanchard, C. M. (2000). The study of emotion in sport and exercise. Historical, definitional, and conceptual perspectives. In Y. L. Hanin (Ed.), *Emotions in Sport* (pp. 3–37). Champaign, IL: Human Kinethics.

Van Der Linden, J., Schoonderwaldt, E., Bird, J., & Johnson, R. (2011). MusicJacket - Combining motion capture and vibrotactile feedback to teach violin bowing. *IEEE Transactions on Instrumentation and Measurement*, *60*(1), 104–113.

van Erp, J. B. F., Saturday, I., & Jansen, C. (2006). Application of Tactile Displays in Sports: where to, how and when to move. In *Proceedings of Eurohaptics* (pp. 105–109).

Vines, J., Clarke, R., & Wright, P. (2013). Configuring participation: on how we involve people in design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'13* (Vol. 20, pp. 429–438). https://doi.org/10.1016/S0142-694X(98)00026-X

Viseu, A., & Suchman, L. (2010). Wearable Augmentations: Imaginaries for the Informed Body. In *Technologized Images, Technologiezed Bodies: anthropological approaches to a new politics of vision* (pp. 161–184).

Wagner, C. R., Stylopoulos, N., & Howe, R. D. (2002). The role of force feedback in surgery: analysis of blunt dissection. In *Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002* (pp. 68–74). IEEE Comput. Soc. https://doi.org/10.1109/HAPTIC.2002.998943

Walmink, W., Wilde, D., & Müller, F. 'Floyd'. (2014). Displaying Heart Rate Data on a Bicycle Helmet to Support Social Exertion Experiences. In *Proceedings of the 8th*

International Conference on Tangible, Embedded and Embodied Interaction - TEI'14.

Weilenmann, A., & Holmquist, L. E. (1999). Hummingbirds go skiing: using wearable computers to support social interaction. In *The 3rd International Symposium on Wearable Computers* (pp. 191–192). IEEE. https://doi.org/10.1109/ISWC.1999.806924

Wheaton, B. (2004). *Understanding lifestyle sports: Consumption, Identity and Difference*. Routledge.

Wiehr, F., & Kosmalla, F. (2016). betaCube – Enhancing Training for Climbing by a Self-Calibrating Camera Projection Unit. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'16*.

Woźniak, P. W., Knaving, K., Björk, S., & Fjeld, M. (2015). RUFUS: Remote Supporter Feedback for Long-Distance Runners. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services* (pp. 115–124). https://doi.org/10.1145/2785830.2785893

Wright, P., & McCarthy, J. (2008). Empathy and experience in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'08* (pp. 637–647). ACM Press. Retrieved from http://portal.acm.org/citation.cfm?doid=1357054.1357156

Young, D. E., Schmidt, R. A., & Lee, T. D. (1991). Skill learning: Augmented Feedback (pp. 558–561).

Zhao, Z., Etemad, S. A., & Arya, A. (2016). Gamification of exercise and fitness using wearable activity trackers. In *Proceedings of the 10th International Symposium on Computer Science in Sports* (pp. 233–240). Springer.

Appendix

List of figures

Climbing Glossary

This glossary compiles the climbing terms that will be used in the following chapters and clarifies their meaning. The definitions have been re-elaborated from those found on Wikipedia. The glossary has been organised into four categories: i) Types of climbing, ii) Activity, iii) Gear, and iv) Rocky Landscape.

Types of climbing

There are many sub-disciplines of climbing. Here, the most common ones and those mentioned in the thesis are described.

Sport climbing - is a form of rock climbing that relies on permanent anchors fixed to the rock (possibly bolts) for protection. While the first climber moves up the wall, s/he has to anchor the rope to these bolts by means of quickdraws (see Gear) in order to protect her/himself.

Bouldering - Ascending boulders or small outcrops with only the use of climbing shoes and a chalk bag. Usually, instead of using a rope, a climber uses a crash pad to avoid injury on falling and a human 'spotter' to direct a falling climber onto the pad.

Trad climbing / mountaineering / alpinism - is a form of climbing without fixed anchors and bolts. Climbers place removable protections such as camming devices, nuts, and other passive and active protections that hold the rope to the rock (via the use of carabiners and webbing/slings) in the event of a fall and/or when weighted by a climber.

Solo climbing or soloing - is a style of climbing in which the climber climbs alone, without somebody belaying them. When free soloing, a serious error is usually fatal as no belay systems are being used.

Activity

Leading vs. climbing in top-rope - A route can be climbed *leading* (i.e. going first) or in *top-rope* (i.e. going after the first climber). There is a great difference between leading and climbing in top-rope in terms of risks and tension involved. When leading, the climber brings up the rope tightened to her harness and has to clip it in the quickdraws in order to protect herself. In the case of falls, the leading climber will fall to the point of her/his last protection. When the leading climber arrives at the top, usually there is a chain where the rope is to be anchored and the climber can be lowered by the belayer. When climbing in top-rope (i.e. after the rope has been brought to the top by a leading climber), the rope comes from above and, in case of falls, the climber will fall just to the extent of the elasticity of the rope.

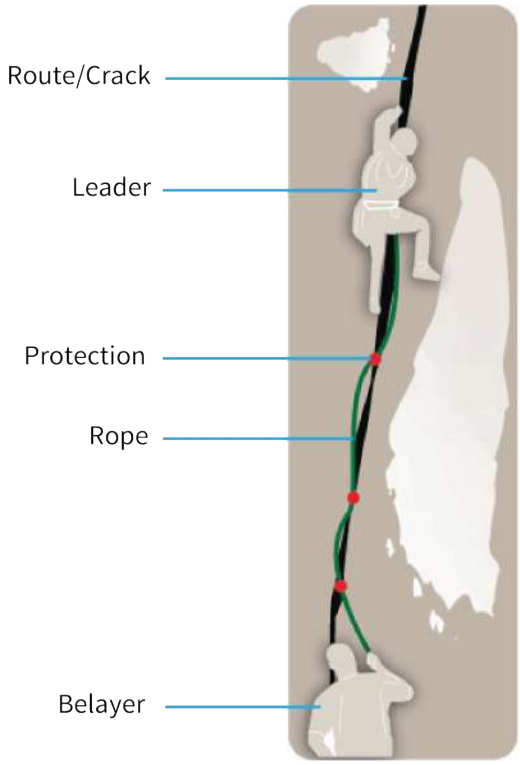


Figure 23. Climbing diagram. Image modified from https://www.designworldonline.com/adrenaline-adventure-engineering/#_

Belay, Belayer, belay device - To belay means to protect a roped climber from falling. It is done by passing the rope through a belay device which adds friction to the rope. Many types of belay devices exist: some of them break the rope (e.g. the Reverso by Petzl), while others have an anti-panic mechanism and are able to block the rope (e.g. Grigri by Petzl).

Give/Take slack – The term 'slack' indicates the portion of rope that is not taut. The belayer has to manage the rope by taking slack to minimise the length of a fall or to give slack when the leading climber needs to pass the rope through the protections.

Resting – When the climber needs to rest, s/he can find a suitable position to rest her/his limbs or can ask the belayer to take in all the slack and just hang on the rope.

Being lowered – After reaching the top and having passed the rope through the last anchor point (the chain), the climber is usually lowered down to the ground by the belayer by cautiously and progressively giving slack through the belay device.

Gear

Here is the list of the essential gear used by climbers and belayers of sport climbing. In Figure 24, the picture in the middle represents the different components of the equipment and the pictures on the sides show how the gear is used. Below, an explanation of the purpose of each piece of gear is presented.

Figure 24. The gear used in Sport Climbing.

1. **Harness** – is worn by both the climber and the belayer and it is used to secure themselves to the rope or to an anchor point.
2. **Quickdraws** – are used by the climber, who puts them in the protections in the wall and passes the rope through them.
3. **Rope** – it connects the climber and the belayer. The belayer manages it by means of a friction device in order to avoid the climber making long and dangerous falls and helping her/him to descend the route.
4. **Grigri®** - Grigri is a registered trademark of Petzl Distribution S.A.S that identifies a friction device used by belayers. It is commonly used by beginners because it is not just a breaking device - it can block the rope and is therefore safer.
5. **Climbing shoes** – Climbing shoes are designed to wrap the feet like gloves. They are covered by a soft rubber beneath and on the sides in order to ensure adherence to the rock wall during all movements. Often, they are curved to direct the climber strength

in the toes and allow her/him to use also the smallest footholds.

Rocky Landscape

Multi-pitch - Multi-pitch routes are long climbing routes which include one or more stops, called ‘belay stations’. Each section of actual climbing between stops at the belay stations is called a pitch When climbing a multi-pitch route (which often means climbing a mountain), the climber goes up and the first pitch is belayed by the belayer standing on the ground, but when the climber arrives at the end of the first pitch, the belayer follows her/him and the first climber belays the second from above. This is repeated for all the pitches of the route.

Chimney - a rock cleft with vertical sides which are mostly parallel and is large enough to fit the climber's body into.

Cards for the Contextual Co-Design Workshop

CONTENUTO: COSA DIRE?

RASSICURAZIONE

Esempi
“Aspetta un attimo”, “Riposati”, “Respira”.

Caratteristiche
Voce calma, suadente.
Volume basso.
Contatto fisico dolce, gentile.

INDICAZIONI

Esempi
“Prova a mettere il piede lì”, “spostati sulla destra”, “tieni il bacino vicino alla parete”.

Caratteristiche
Parole scandite bene.
Gesti con il corpo per mimare, indicare e far imitare.

INCORAGGIAMENTI

Esempi
“Dai!”, “Provaci!”, “Dai che ce la fai!”.

Caratteristiche
Esclamazioni brevi.
Volume alto.
Tenere i pugni stretti, battere le mani.

CONGRATULARSI

Esempi
“Olé!”, “Bravo!”, “Grande!”.

Caratteristiche
Esclamazioni brevi, espresse a volume alto, con tono gioioso.
Sorrisi, appluasi, pacche sulle spalle.

RICHIEDERE ATTENZIONE

Esempi: “Ci sei?”, “Tienimi eh!”, “Guardami!”.

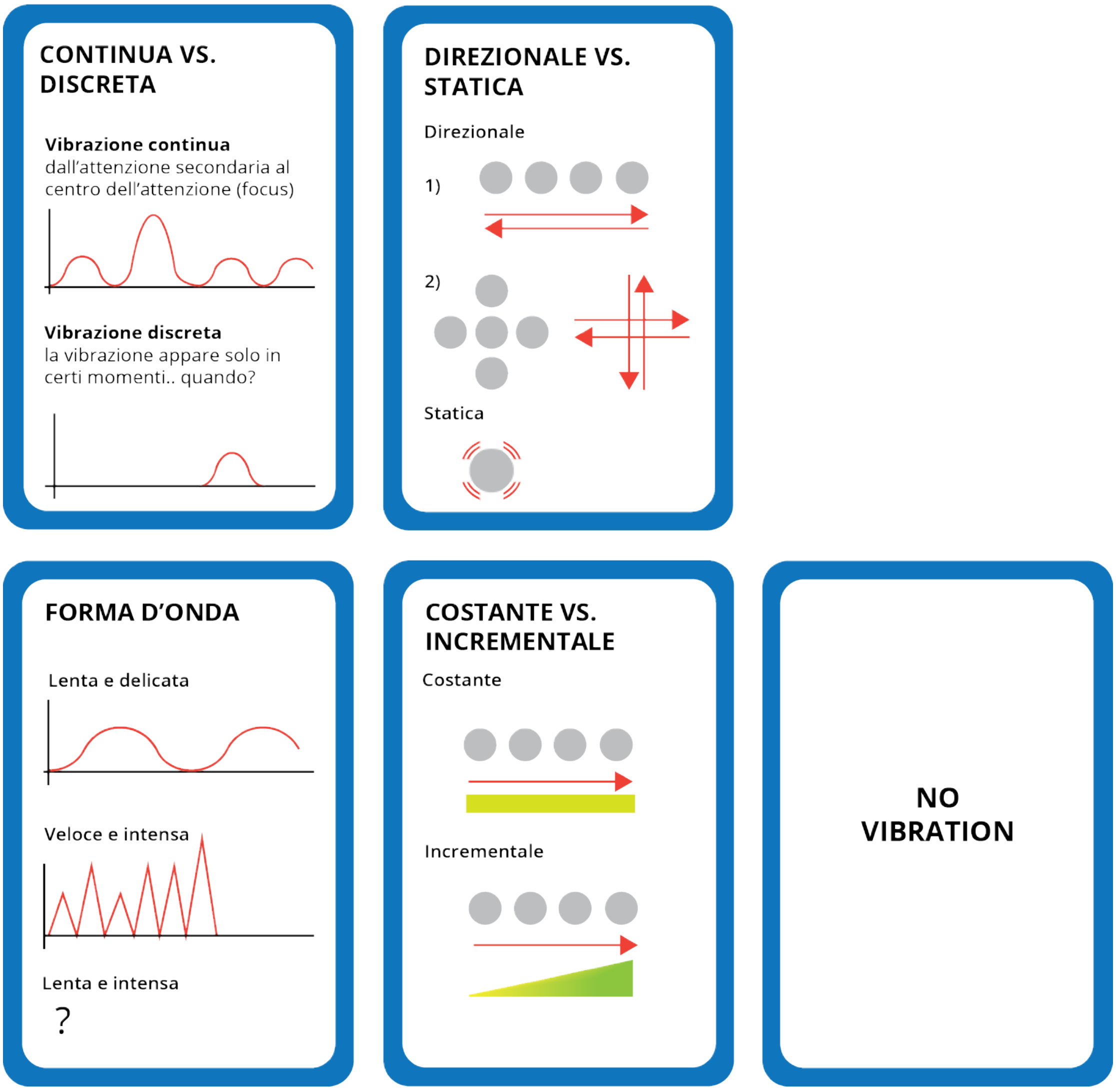
Caratteristiche
Tono assertivo, insistente.
Contatto visivo per assicurarsi di essere stati capiti.

COMANDI

Esempi
“(Dammi) Corda!”, “Recupera!”, “Blocca!”.

Caratteristiche
Esclamazioni brevi, urlate, serie. Tono assertivo.
Contatto visivo per assicurarsi di essere stati capiti.

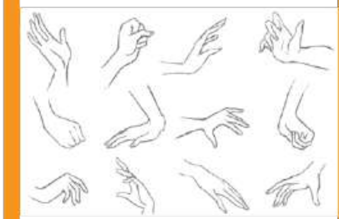
POSSIBILITA' COMUNICATIVE DELLA VIBRAZIONE: COME COMUNICARE UN CERTO MESSAGGIO?



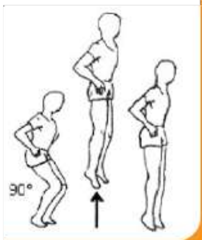
INPUT: COME VIENE INVIATO UN MESSAGGIO VIBROTATTILE?

PREMERE/TOCCARE

GESTI



MOVIMENTI



SGUARDO

DOVE?

INCORPORATO IN UN WEARABLE DEVICE

INCORPORATO NELL'ABBIGLIAMENTO

INCORPORATO NEL MATERIALE